The role of object semantics in guiding overt attention of younger and older adults, and AD patients

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Abstract

For decades, vision research has investigated the influence of object semantic information on visual attention by examining eye movements. However, it has provided contrasting evidence about the extent to which object semantics can be processed in the extra-fovea and guide gaze, as well as about the temporal dynamics of such processing. Moreover, it is still unclear whether and how healthy and pathological ageing impairs the ability to process semantic information and to use it for attentional guidance. Finally, how the high-level semantic features of objects interact with their low-level visual features, e.g., visual saliency, in guiding eye movements and how their interplay changes according to the type of task performed are still debated. Six experiments in this thesis contribute novel findings to this discussion by examining the influence of object-to-object semantic relatedness, as well as visual saliency, on behavioural and eye-movement responses of different populations of participants, i.e., young adults, healthy older adults, and people with Alzheimer's disease (AD), while they inspect objects arrays during a visual search task and a memorization task.

In Chapter 1, I review the relevant research literature, whereas in Chapter 2, I present the methodology used throughout the experiments of this thesis. Chapter 3 describes three visual search experiments carried out with younger (Experiments 1 and 2) and healthy older participants (Experiment 3). I found that younger and older adults looked earlier and for longer at a critical object when it was semantically unrelated than related to the other objects in the array, both when it was the search target (target-present trials) and when

it was a target's semantically related competitor (target-absent trials). For the younger adults only, semantic relatedness effects manifested already during the very first fixation after array onset. I conclude that the semantic information of objects can be processed in extra-foveal vision so early to guide initial eye movements. Older adults process object semantics in the extra-fovea to orient gaze as younger adults do, although there might be age-related differences in the time-course of such processing.

In Chapter 4, I used the same visual search task to compare the eye-movement behaviour of AD patients and healthy age-matched controls (Experiment 4). I found that both groups looked at the critical object earlier when unrelated than related to the other objects, with no difference among groups. In contrast to previous findings from the literature pointing at a complete disruption of semantic memory in AD, I argue that object semantic processing can be preserved in AD patients in specific circumstances.

Visual saliency did not affect eye movements during any of the visual search experiments. This finding is consistent with previous studies showing that saliency plays a marginal role in attentional control during search, while exerting a stronger influence during non-cued visual tasks, such as memorization. In Chapter 5, two experiments monitored the eye movements of younger (Experiment 5) and older adults (Experiment 6) who were asked to freely inspect the same object arrays, in preparation for immediate verbal recall. I found that, in both younger and older adults, the critical object was more likely to be recalled when semantically related than unrelated to the distractors. The effect of semantic relatedness on memory was explained by differences in the allocation of overt attention, with semantically related critical objects being more likely to be fixated than semantically unrelated ones, although in older adults only, other cognitive mechanisms seemed to be involved, e.g., semantic priming. Visual saliency had a significant effect neither on memory nor on eye movements, presumably because of methodological limitations of the experimental design.

All in all, the findings of this thesis pose a challenge to current models of visual attention by highlighting the primary role of extra-foveal semantic processing in guiding visual attention, and provide evidence that such processing is preserved in healthy ageing and AD. By influencing oculomotor behaviour, semantic information strongly affects our ability to search for objects and/or to store them in memory.

Lay summary

We live in a rich, complex and noisy world that we explore every day by constantly moving our eyes. Eye movements are necessary because detailed information about the objects surrounding us can be acquired only in the fovea, a small, central, high-resolution region of our retina. The objects to be foveated are selected from the periphery of the retina, in extra-foveal vision, which is responsible for low-resolution visual processing.

An interesting question in vision research is what are the features of the objects that are processed in extra-foveal vision and used to guide our visual attention. Object visual features, such as colour and shape, exert a huge impact on eye movements. An object attracts our gaze because it is salient, e.g., a conspicuous green jacket in a wardrobe full of black suits, or because it is visually similar to another object, e.g., when searching for a red apple, our eyes are preferentially moved towards a red ball rather than a green book. Critically, objects are defined not only by visual features, but also by semantic features, for instance, the semantic category they belong to. Previous studies showed that observers who are asked to search for a target, e.g., motorcycle, in arrays of objects, preferentially move their eyes towards semantically related, e.g., helmet, than unrelated objects, e.g., glass. Evidence of semantic relatedness effects indicates that the semantic features of objects can be accessed in extra-foveal vision and used to guide visual attention. However, whether extra-foveal semantic processing can occur so early to influence initial eye movements is still debated. Also, little is known about the extent to which extra-foveal semantic processing and semantic guidance of eye movements are impaired in healthy and pathological ageing, i.e., Alzheimer's disease (AD). Finally, how object semantic features interact with their visual features in guiding eye movements and how their influence changes according to the type of visual task to be performed is still unclear. The current thesis addresses these issues with a series of experiments which examined the influence of semantic relatedness and visual saliency information on the eye movements of younger, older adults, and AD patients performing a search and/or a memorization task on object arrays. The visual search experiments found evidence of semantic relatedness effects on initial eye movements in younger adults, indicating that object semantic information can be accessed early in extra-foveal vision and promptly guide our attention. Effects of semantic relatedness on eye movements during search were also found in older adults and AD patients, suggesting that they can rely on extra-foveal semantic processing to guide visual attention, as younger adults do. Finally, semantic relatedness also influenced eye movements during object memorization. When an object is presented together with semantically related objects is more likely to be looked at, and then remembered, compared to when it is displayed with semantically unrelated objects, in both younger and older adults.

The core findings of this thesis highlight the predominant role played by the semantic features of objects in guiding the allocation of overt attention in early and late adulthood, and in pathological populations, i.e., AD, beyond the influence exerted by their visual features.

Declaration

I have read and understood The University of Edinburgh guidelines on plagiarism and declare that this dissertation is of my own work, except where I indicate otherwise in the thesis; that I have made a substantial contribution to the chapters written as a member of a research group; and that the work has not been submitted for any other degree or professional qualification.

The work related to Experiments 1 and 2 in Chapter 3 was previously published in Attention, Perception, and Psychophysics as "*Extra-foveal processing of object semantics guides early overt attention during visual search"* by Francesco Cimminella, Sergio Della Sala, and Moreno Ignazio Coco.

The work related to Experiment 4 in Chapter 4 has been submitted recently for publication by Francesco Cimminella, Giorgia D'Innocenzo, Sergio Della Sala, Alessandro Iavarone, Caterina Musella, and Moreno Ignazio Coco. The experiment is based on a design that I developed, and data that I collected and analysed. Moreno Ignazio Coco contributed to the implementation of the experiment in OpenSesame and, together with Giorgia D'innocenzo and Sergio Della Sala, to the writing of the Introduction and Discussion, whereas Alessandro Iavarone and Caterina Musella helped with the recruitment of participants.

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Summer is coming.

1 General Introduction

1.1 Eye movements are not random

When we perform a visual task, whether it is searching for our wallet on a cluttered desk, looking at a painting in an art gallery, or inspecting items displayed in a shop to memorize them for a later, and cheaper, online purchase, we execute rapid eye movements, called saccades, approximately three times each second. Between saccades, our eyes remain relatively still during a period of time, called fixation, lasting between 200-300 ms (Rayner, 1998, 2009). Eye movements are necessary to overcome the physiological limitations of our visual system. The visual field can be divided into three regions, going from the centre to the periphery of the retina: (1) the fovea, which subtends a visual angle of 1° eccentricity; (2) the parafovea, which stretches out to 4-5°; and (3) the periphery, which extends beyond the parafovea and covers the rest of the visual field (Larson & Loschky, 2009; Rayner, 1998, 2009). Due to the nature of the retina, visual acuity is the highest in the fovea, which is responsible for high-resolution vision and diminishes with increasing retinal eccentricity (Strasburger, Rentschler, & Jüttner, 2011). Given the small dimensions of the fovea and the size and complexity of the visual environments we inhabit, eye movements are executed to bring in turn local regions of the visual environment onto the fovea, so that they can be fully perceived. The local regions to be foveated are selected in the parafovea and the periphery, i.e., in extra-foveal vision, where a great deal of useful, but low-resolution, visual information is accrued

(Rayner, 2014; Rosenholtz, 2016; B. Wolfe, Dobres, Rosenholtz, & Reimer, 2017).

One of the fundamental questions addressed in vision research over the last 40 years has been what guides this selection. In other words, what type of information available in extra-foveal vision guides the allocation of attention to one visual region over another? This question has generated a great deal of studies and debate, even though researchers generally agree on distinguishing two main forms of guiding information: exogeneous, stimulus-driven information (i.e., bottom-up), and endogenous, knowledge-based information (i.e., top-down) (see Ruz & Lupiáñez, 2002; J. M. Wolfe & Horowitz, 2004, 2017; Wu, Wick, & Pomplun, 2014, for reviews). When attention is guided by bottom-up information, eye movements are automatically drawn to the local regions of a visual environment by virtue of their distinctiveness. A striking visual stimulus, such as the vividly coloured object in Figure 1, immediately captures the observer’s gaze to its spatial location, without effort and independently of his/her intentions. Instead, when attention is guided by top-down information, eye movements are directed according to the observer’s knowledge and expectations and the demands imposed by the task. The allocation of overt attention is slow, effortful and under the control of the observer, as when asked to search for the small, black “+” superimposed over one of the objects in Figure 1.

Whether captured by bottom-up information or modulated by top-down information, eye movements are not random. Instead, several sources of

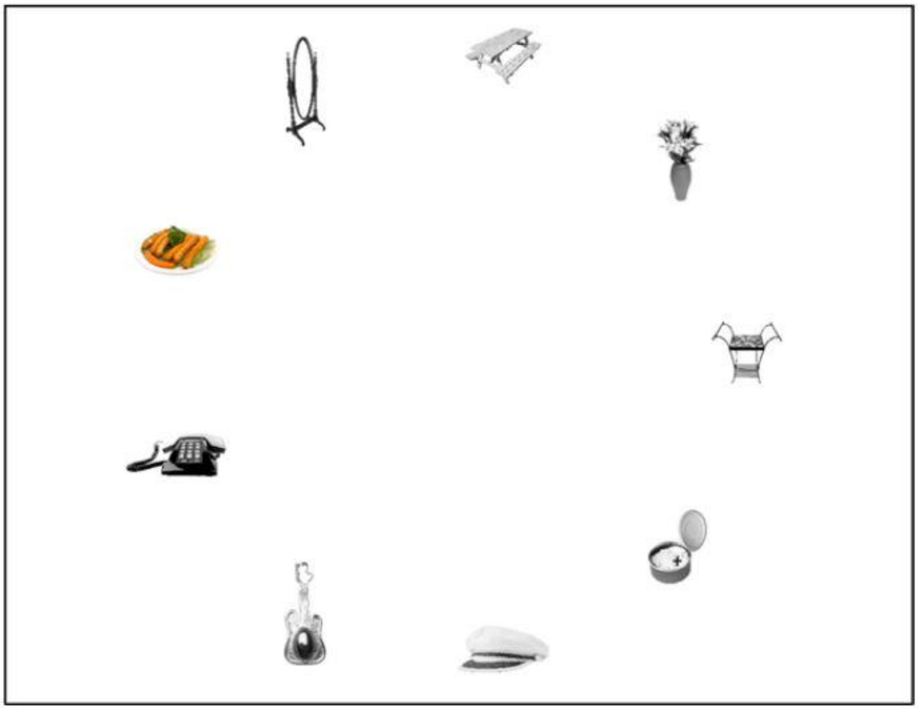


Figure 1. Overt attention is involuntarily captured by the coloured singleton, carrots in a plate, which immediately pops out among the non-coloured objects, i.e., “bottom-up attention”. By contrast, finding the small, black “+” located on the opened can requires time and active attentional control by the observer, i.e., “top-down attention” (taken from Chen & Zelinsky, 2006).

information are available in extra-foveal vision to guide them and maximize the way we perceive and understand the world around us.

1.2 Low-level visual feature guidance

Most computational models of visual attention attribute a key role to the low-level, or visual, features of stimuli (e.g., colour, shape, orientation), in explaining eye-movement behaviour in complex visual contexts, e.g., arrays of objects or photographs of naturalistic scenes (Itti & Koch, 2000; Parkhurst, Law, & Niebur, 2002; Torralba, Oliva, Castelhano, & Henderson, 2006; Zelinsky, 2008; Zelinsky, Adeli, Peng, & Samaras, 2013). These models evolved out of earlier theories, such as the seminal Feature Integration

Theory (FIT) by Treisman and Gelade (1980) which assumes a two-stage architecture for visual perception. During the first stage, visual features are processed pre-attentively (before being foveated), independently, and in parallel (simultaneously) across the visual field. In the second stage, visual attention is directed serially to one stimulus location at a time to bind these separable features together into unitary stimuli. This assumption was tested in a series of visual search experiments, where participants performed feature search and conjunction search tasks on arrays of simple stimuli (i.e., letters). In feature search, the target differed from distractors by a single visual feature, such as colour (e.g., a red X among green Xs), whereas in conjunction search, the target differed from distractors in terms of a combination of two or more features, such as shape and colour (e.g., a red X among green Xs and red Os). Treisman and Gelade found that, in the feature condition, the target was detected almost immediately, independently of the number of the distractors in the arrays, i.e., set size, a phenomenon known as “pop-out effect”. Instead, in the conjunction condition, search was slower, and the time needed to locate the target, i.e., response time, increased as the set size increased. The authors interpreted the evidence of pop-out effects in feature search to indicate that a visual context is initially coded along a set of separable visual features, registered pre-attentively and in parallel across the visual field. Instead, the increase in search times as function of the set size, observed in conjunction search, would indicate that attention is directed serially in the visual context to inspect visual stimuli in turn, bind their separable features, and eventually, take a target/distractor decision.

A curious characteristic of the standard FIT (Treisman & Gelade, 1980) is that the pre-attentive, parallel stage does not have any influence on the subsequent, serial stage (but see Evans & Treisman, 2005; Treisman, 2006; Treisman & Sato, 1990, for later developments of the original model). That is, when searching for a target defined by a conjunction of features, none of the information gathered during the pre-attentive, parallel stage is used to guide visual attention, which would be thus allocated serially on every stimulus in the visual context until the target is found (J. M. Wolfe, Cave, & Franzel, 1989). As an alternative to FIT, Wolfe and colleagues later developed a two-stage model of visual search behaviour on arrays of simple stimuli (e.g., bi-dimensional bars varying in colour, orientation, and size), the Guided Search (GS) model (see J. M. Wolfe et al., 1989, for the original model; and J. M. Wolfe, 1994, 2007; J. M. Wolfe & Gancarz, 1996, for later refinements). The core of the GS model is that the allocation of visual attention is guided by the output of earlier pre-attentive, parallel processes. At the onset of the search array, a pre-attentive, parallel processing of the visual features of stimuli takes place across the visual field. For each feature type, separate topographical maps, with regions corresponding to areas of the visual field, are generated, called feature maps. Regions within each feature map are activated in a bottom-up manner, i.e., a region is activated based on the difference between it and the neighbouring regions, and/or top-down manner, i.e., a region is activated if it shares visual features with the target (e.g., red, but not green, regions in the colour feature map are activated when searching for a red target). The feature maps are then summed to form a pre-attentive, topographical map, called activation map, which is used to guide attention. In the subsequent, serial stage of visual search, attention will be allocated to areas of the visual field corresponding to the regions of the activation map with the highest activation values. Figure 2 shows the architecture of the GS model.

Since the formulation of the FIT and GS models, there has been a proliferation of computational models of attention relying on low-level visual features. Contrary to earlier theories, these models are designed to work with more complex visual contexts, such as arrays of real-world objects and photographs of naturalistic scenes, and provide a more biologically plausible explanation of how visual information is accessed from the world and used to guide attention. Similarly to earlier theories, they are based on the concept of a topographical map of prioritised activity which combines information from separate feature maps and is used to generate predictions as to where attention, and eye movements, should be directed when exploring a visual context. Critically, these models differ among each other on what type of features of a visual context influence the activity in the map and thus make different predictions about what areas of the visual field are more probable to be selected for fixation.

One of the most prominent models of bottom-up visual attention is the visual saliency model by Itti and Koch (2000). In this model, separate feature maps, called conspicuity maps, are first computed for three low-level visual

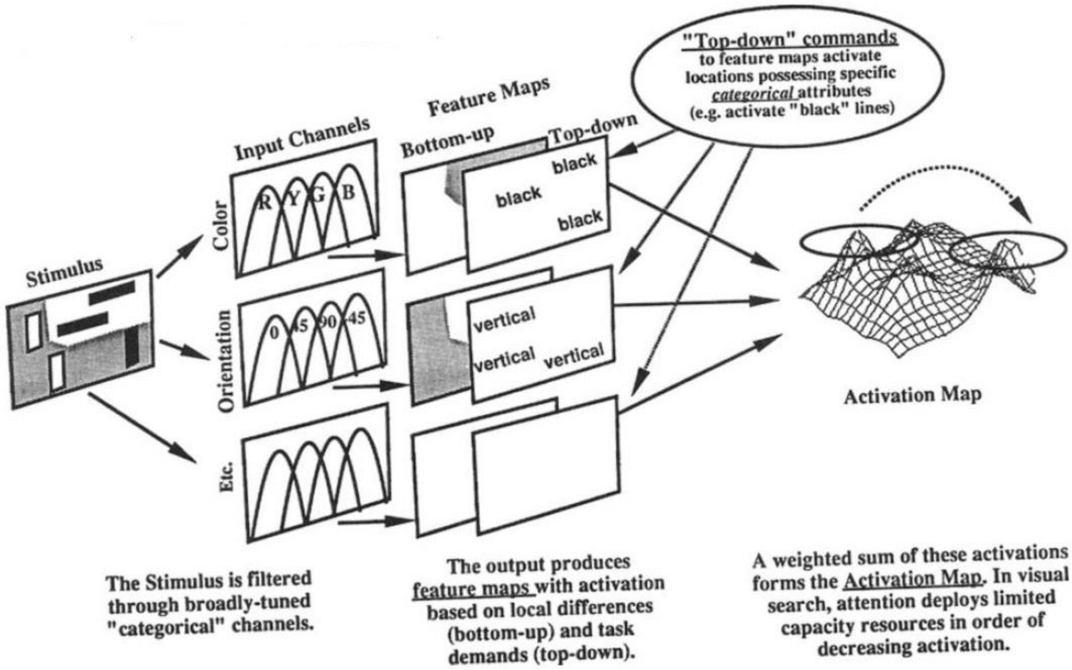


Figure 2. The architecture of the GS model (taken from J. M. Wolfe, 1994).

features of the visual context, i.e., colour, intensity, and orientation. Regions in the conspicuity maps corresponding to areas of the visual context with high saliency, e.g., areas differing from their surroundings by variations of colour, intensity, or orientation, receive higher activation. The saliency information from the separate conspicuity maps is combined into one global measure of saliency in the saliency map. This is a topographical representation of the areas of the visual context, where each area is assigned a different saliency value. Attention is predicted to move to the area having the greatest saliency value in a winner-take-all algorithm. Once the area has been inspected, its saliency value is reduced by a process of inhibition of return that allows attention to be disengaged from this area and move to the next most salient one. The visual saliency model by Itti and Koch is a purely bottom-up model of visual attention, where eyes are predicted to move from the most to the least salient areas of the visual context, independently from the current task goals. Visual saliency is a good predictor of visual attention when there are no specific target objects set by the task, e.g., free viewing (e.g., Parkhurst et al., 2002), memorization (e.g., Underwood & Foulsham, 2006; Underwood, Foulsham, van Loon, Humphreys, & Bloyce, 2006), and visual search tasks where search is not cued to any specific target object, and such target differs in visual features, e.g., colour, from other homogeneous distractors (J. M. Wolfe, Butcher, Lee, & Hyle, 2003). In these tasks, salient regions of a scene are looked at earlier and for longer than non-salient ones because they are regarded as interesting and informative, i.e., they carry more low-level information, and more attentional resources are needed to fully process them (Coco, Malcolm, & Keller, 2014; Elazary & Itti, 2008; Masciocchi, Mihalas, Parkhurst, & Niebur, 2009; Underwood & Foulsham, 2006).

However, when the identity of the target is cued prior to the search, through a word label or a visual object, bottom-up visual saliency is largely ignored (Chen & Zelinsky, 2006; Einhäuser, Rutishauser, & Koch, 2008; Foulsham & Underwood, 2007; Henderson, Brockmole, Castelhano, & Mack, 2007; Underwood & Foulsham, 2006). This is not surprising: looking at the bright, shiny, and colourful objects in a room when searching for your wallet is ineffective and time-consuming. In such situations, knowledge of the appearance of the search target, e.g., rectangular, black, and small, is more useful. Zelinsky (2008) proposed a top-down model of target acquisition during search, based on the precise knowledge of target's visual features, the Target Acquisition Model (TAM, see also Zelinsky et al., 2013, for an extension of the original model to search for categorically defined targets). According to this model, overt attention is guided to regions of the visual context that contain high-level, knowledge-based information related to the search target. TAM takes two images as input, one of the search target, and one of the visual context, and attempts to locate the target in the visual context by generating a sequence of eye movements that eventually align a simulated fovea with the target. At the start of the sequence, the coordinates of the simulated fovea are set to the centre of the visual context, which is transformed to reflect retinal acuity limitations, whereby the central areas of the visual context appear sharp, while eccentric areas blurred. Then, a priority map, called target map, is created by correlating a vector of colour, orientation, and scale-selective filter responses obtained for the target with filter response vectors derived for every pixel location in the retina-transformed visual context. Each point on the target map represents an estimate of the visual similarity between the target and each location in the visual context (see Figure 3, for an example of a target map). The point of highest correlation in the map, i.e., the hotspot, corresponds to the most likely target location. If the hotspot correlation exceeds a high detection threshold, a target is detected without moving the simulated fovea. However, if the hotspot correlation is lower than the detection threshold (e.g., the hotspot pattern might correspond to the location of the target but peripheral blurring, simulating retinal acuity limitations, might lower its correlation), the simulated fovea is moved to its coordinates. At these coordinates, a new retina-transformed version of the visual context is created, and the sequence

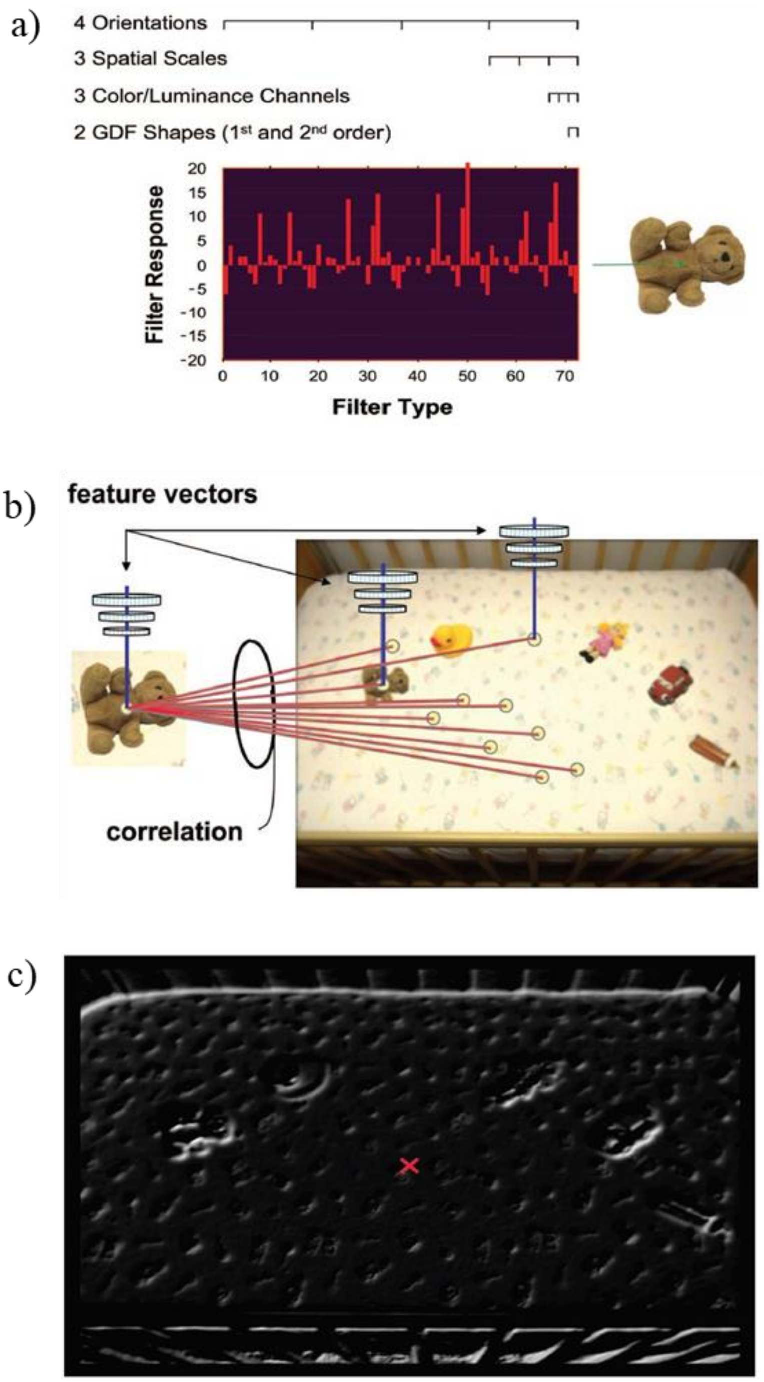


Figure 3. The generation of a target map. a) A 72-dimensional feature vector is used to represent visual information for the target object, i.e., a teddy bear. b) The feature vector representing the target is correlated with feature vectors from every pixel location in the retina-transformed visual context (note that each object is slightly blurred). c) The target map is generated, with brighter points indicating higher correlations, i.e., greater visual similarity between the target and corresponding location in the visual context (adapted from Zelinsky, 2008).

starts again (an inhibition-of-return mechanism is also activated to prevent the simulated fovea to be trapped in the same locations). Contrary to the Itti and Koch's model (2000), Zelinsky's TAM (2008) assumes a guidance process driven by the knowledge of the target visual features, and thus provides a top-down account of attentional control. Its predictions have been confirmed by several studies showing that when searching for a cued target (e.g., a red ball), observers preferentially look at visually similar (e.g., a red apple) than dissimilar (e.g., a yellow banana) objects, since the very first fixation (e.g., Alexander & Zelinsky, 2011; Schmidt & Zelinsky, 2009).

1.3 High-level semantic feature guidance in naturalistic scenes

Despite their differences, both earlier (Treisman & Gelade, 1980; Treisman & Sato, 1990; J. M. Wolfe, 1994; J. M. Wolfe et al., 1989; J. M. Wolfe & Gancarz, 1996) and more recent models (Itti & Koch, 2000; J. M. Wolfe, 2007; Zelinsky, 2008; Zelinsky et al., 2013) of visual attention assume that attention is guided purely by the low-level visual features of stimuli. However, real-world objects are defined not only by low-level visual features, such as shape and colour, but also high-level features, such as their meaning and semantic relationships among them, and their role in the allocation of overt attention is currently highly debated. A common way to investigate the semantic capture of attention has been to manipulate the semantic relationship between an object and the scene background in which it is embedded, such that it is either semantically consistent or inconsistent with the scene.

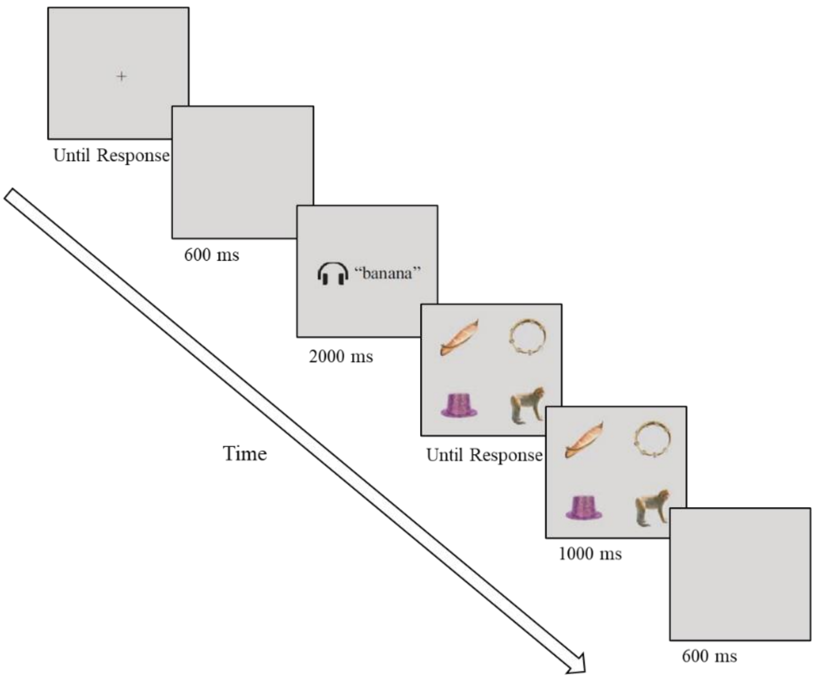
In a seminal study on visual perception, Loftus and Mackworth (1978) instructed participants to freely inspect drawings of naturalistic scenes in preparation for a later memory recognition task. They found that objects semantically inconsistent (e.g., an octopus) with the scene (e.g., a farm) were fixated for the first time earlier than consistent ones (e.g., a tractor), already after the first fixation on the scene. They also found that the eye saccades towards the inconsistent objects averaged between 6.5 and 8 degrees of visual angle in amplitude, suggesting that object semantic information could be processed early in extra-foveal vision and guided initial eye movements. These findings were not replicated by later studies (e.g., De Graef, Christiaens, & D'Ydewalle, 1990; Henderson, Weeks, & Hollingworth, 1999). Using a similar task, where participants were asked to inspect scene drawings in preparation for a memory task, Henderson et al. (1999) reported that semantically inconsistent objects were fixated as early as consistent ones, with an average saccade amplitude of 3 degrees of visual angle. Object semantic information affected eye movements only upon fixation, with semantically inconsistent objects being fixated for longer than consistent ones. The authors explained the different results by arguing that in Loftus and Mackworth (1978) semantically incongruent objects might have been more visually salient than consistent ones. Thus, overt attention might have been captured by low-level visual rather than high-level semantic information. Also, Henderson et al. (1999) noted that the scenes they used were more complex, i.e., contained more objects, than those presented by Loftus and Mackworth (1978). The use of sparser scenes, containing fewer objects and a larger amount of blank space, might have increased the average saccade amplitude, given that observers are more likely to saccade to objects than empty space.

Since then, a great deal of studies has investigated the effects of scene-object inconsistencies on eye-movement behaviour on photographs of complex, naturalistic scenes. These studies, which controlled or manipulated low-level visual saliency, provided contrasting conclusions. Replicating Henderson et al. (1999), some researchers showed that inconsistent objects are fixated for longer but not earlier than consistent ones, and claimed that object semantic information cannot be processed in extra-foveal vision to a degree sufficient to affect attentional capture (Võ & Henderson, 2009, 2011). Instead, other studies found that semantic inconsistent objects attract earlier, and longer, fixations compared to consistent ones (Bonitz & Gordon, 2008; Brockmole & Henderson, 2008; Cornelissen & Võ, 2017; LaPointe & Milliken, 2016; Underwood & Foulsham, 2006; Underwood, Templeman, Lamming, & Foulsham, 2008; but see Coco et al., 2014; Spotorno & Tatler, 2017, for evidence of attentional prioritisation of semantic consistent objects). Inconsistent objects would be prioritised because they are in conflict with the semantic of the scene and more attentional resources are needed to solve this conflict, or because they are more difficult to identify, and thus became the focus of attention (e.g., Bonitz & Gordon, 2008). Altogether, these studies support the Loftus and Mackworth's (1978) interpretation of an extra-foveal capture of overt attention by object semantic information.

The inconsistencies across studies might be due to the intrinsic complexity of the scenes used as experimental stimuli. Henderson and Hollingworth (1999) define a scene as “a semantically coherent (and often nameable) view of a real-world environment comprising background elements and multiple discrete objects arranged in a spatially licensed manner”. In a single glance, observers can identify the semantic category of a scene, i.e., scene gist (e.g., a kitchen, Greene & Oliva, 2009; Oliva & Torralba, 2006), and then use their knowledge about the scene type to decide where to look (see Wu et al., 2014, for a review). For example, when searching for a target, scenes provide information about possible target locations, i.e., top-down contextual information, which can be used to deploy attention (Castelhano & Heaven, 2011; Castelhano & Henderson, 2007; Malcolm & Henderson, 2010; Neider & Zelinsky, 2006). Contextual information benefits search for consistent, but not inconsistent target objects, which could contribute to the failure to observe guidance towards inconsistent objects in certain studies (e.g., Võ & Henderson, 2009, 2011). Moreover, naturalistic scenes tend to be cluttered, with objects displayed very close to each other. Visual crowding degrades peripheral vision, i.e., observers identify more easily an object in the periphery of the visual field when it is isolated compared to when it is flanked by other objects and the flankers are sufficiently close by (Pelli, Palomares, & Majaj, 2004; Pelli & Tillman, 2008; Rosenholtz, 2016). The use of cluttered scenes in some studies (e.g., Henderson et al., 1999) might have hindered the processing of the semantic features of objects in extra-foveal vision, thus reducing or eliminating any attentional prioritisation of inconsistent objects (Bonitz & Gordon, 2008). A solution to these problems could be the use of arrays of standalone objects. As opposed to naturalistic scenes, objects on arrays are arranged on a blank background and can be easily separated, making easier for observers to select objects to fixate based on their semantic features.

1.4 High-level semantic feature guidance in object arrays: evidence from visual search studies

More consistent evidence of semantic guidance of overt attention comes from the visual search literature on object arrays, where the semantic relationship among objects, i.e., object-to-object semantic relatedness, is manipulated, instead of the scene-object semantic consistency. Using object arrays, Moores, Laiti, and Chelazzi (2003) and Belke, Humphreys, Watson, Meyer, and Telling (2008) showed that, when searching for a target cued by a text label (e.g., motorcycle), initial eye movements are directed more often to semantically related (e.g., helmet) than semantically unrelated objects (e.g., glass), especially on target-absent trials. These findings indicate that object semantics are processed rapidly in extra-foveal vision and guide early overt attention during search. However, Daffron and Davis (2016) claimed that this evidence might have been confounded by the repeated exposure of the stimuli to the participants. For example, in Belke et al. (2008), participants inspected the visual stimuli (line drawings of objects) before the experiment began, thus raising the concern that eye movements were guided by the memory of the visual features of the stimuli rather than by their semantics. Also, de Groot, Huettig, and Olivers (2016) cast doubt on Moores et al. (2003) and Belke et al.'s (2008) findings using a similar task, where participants searched for a target (e.g., a banana) in target-absent 4-object arrays comprising a semantic competitor (e.g., a monkey), a visually similar competitor (e.g., a canoe) and two more unrelated distractors (e.g., tambourine and hat) (See Figure 4a for a representative example of the materials and experimental procedure). De Groot et al. (2016) presented each stimulus only once and, by analysing the fixation location as a function of time, found that overt attention was guided towards semantically related objects, but later than towards visually similar objects (See Figure 4b for a visual representation of the original data). Also, the temporal dynamics of the semantic guidance did not change when visual competitors were removed from the arrays in a follow-up experiment. These results underline the primary role played by visual features in guiding search, and despite supporting previous evidence of extra-foveal capture of overt attention by semantic features in object arrays (Belke et al., 2008; Moores et al., 2003), they question its timing. Interestingly, in a more recent article, Nuthmann, de Groot, Huettig, and Olivers (2019) re-analysed the original data from de Groot et al. (2016), by computing the latency to first fixation, i.e., the time needed to fixate on an object for the first time, and the probability of immediate fixation, i.e., the probability of the very first fixation to fall on an object. They found shorter search latencies and a higher probability of first a)



b)

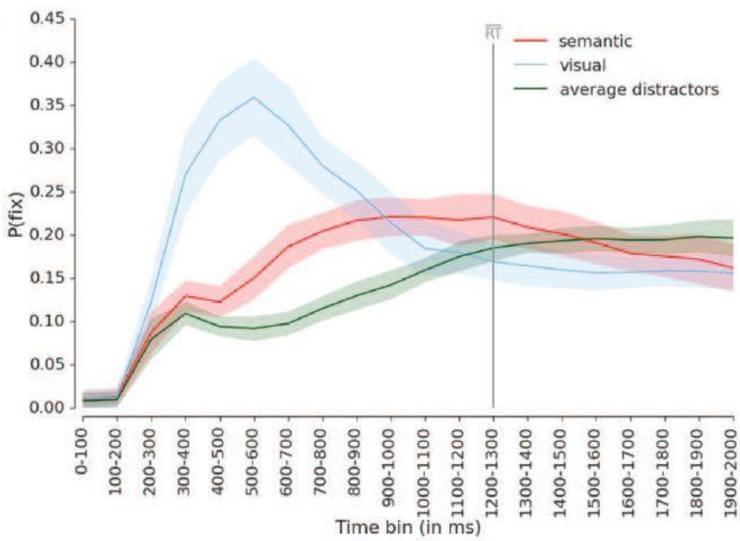


Figure 4. a) shows an example of materials and experimental procedure. Each trial started with a drift correction, after which the screen turned blank for 600 ms. This was followed by the auditory presentation of the target word, and after 2000 ms, of the search array which was displayed until participants provided a present/absent response. The array remained on the screen for 1000 ms after the response, and was followed by a blank screen for 600 ms; b) shows the absolute fixation proportions toward the visual competitor, the semantic competitor, and the average of the neutral distractors as a function of time. A period of 2,000 ms after the presentation of the search array was divided into 20 bins of 100 ms. For each time bin, fixation proportions were computed as the percentage of the time in the bin that participants fixated on a certain object (adapted from de Groot et al., 2016).

fixation for semantically related competitors than unrelated distractors, indicating that object semantics can guide initial eye movements from extra-foveal vision. They also found that the time to first fixation was longer for semantically related than visually related competitors, which were also more likely to receive the very first fixation after array onset, suggesting a stronger influence of visual information, than semantic information, on attentional orienting.

Nuthmann et al. (2019) provided strong evidence of semantic guidance of initial eye movements during a search task on object arrays. In Chapter 3 of the current thesis, I used a new experimental paradigm to provide further evidence of the time-course of extra-foveal semantic processing and its impact on early overt attention of young adults performing a visual search task in object arrays (Experiments 1 and 2). In my task, participants were presented with a cue word for a target object, i.e., target name, to be searched in an array displaying a critical object plus 2, 4 or 6 additional semantically homogenous distractor objects (e.g., all vehicles). I manipulated the visual saliency of the critical object (salient or non-salient) as well as its semantic relatedness (related or unrelated) with the distractors (see Figure 5 for the experimental design and materials and refer to Chapter 2 for more details). Each object was located with an eccentricity of 9.62° of visual angle from the centre of the screen, i.e., it was placed in extra-foveal vision. In Experiment 1, the cue word referred to an object that did not appear in the array (target-absent), and it was semantically related to the critical object (e.g., the cue word was airplane and the critical object was instead a

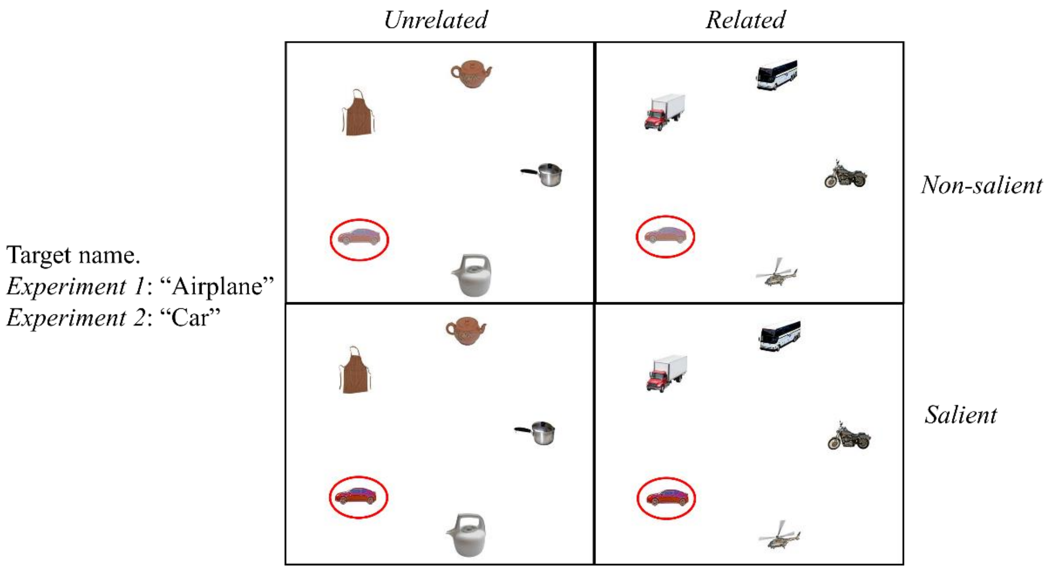


Figure 5. Experimental design and example of an object array, which included a critical object (e.g., car, highlighted in red) plus either 2, 4, or 6 distractors. In Experiment 1, the target name cued an object that was not visually depicted in the array (target-absent), but it was semantically related to the critical object and thus to the distractors in the semantically related but not the unrelated condition (e.g., airplane). In Experiment 2, the target name cued the critical object as the target (target-present).

car). Instead, in Experiment 2, the cue word referred to the critical object, which was the target of the search (target-present).

My manipulation of semantic relatedness differs from previous studies (de Groot et al., 2016; Nuthmann et al., 2019), and I believe that this aspect of the experimental design may increase the probability to observe effects of semantic guidance on early overt attention. In these studies, a competitor object semantically related to the target was presented together with distractors that were semantically unrelated to the target, to the semantic competitor, and among themselves. A seminal study by Duncan and Humphreys (1989) showed that when distractors differ homogenously from the target on a target-defining visual feature (e.g., the colour), the guidance of such feature on directing overt attention is very strong. When distractors are instead more heterogeneous, then such a feature has a weaker effect. I followed the same logic in my experiment but applied it to semantic relatedness. As opposed to de Groot et al. (2016) and Nuthmann et al. (2019) who investigated semantic guidance effects on target-absent object arrays only, I also compared search performances on target-absent and target-present arrays to examine whether effects of semantic relatedness varied according to the presence of the target. As suggested by Huettig and Altmann (2005), and Huettig and Mcqueen (2007), the presence of the target in the array should reduce the effects of semantic relatedness because participants might rely more on visual information to facilitate search. Additionally, I manipulated the size of the distractor set in my experimental design to examine if, and to what degree, semantic processing was affected by the number of distractors in the arrays or occurred in parallel across the visual field, i.e., semantic pop-out effect, as for the search of simple low-level visual features (e.g., Treisman & Gelade, 1980). Finally, the manipulation of the visual saliency of the critical object allowed me to examine the influence of low-level visual information on overt attention and exclude that it may play a role in a cued visual search on object arrays, as previously shown by (Chen & Zelinsky, 2006).

Evidence of semantic relatedness effects on early overt attention has important theoretical implications for vision research. It would pose a challenge to visual attention models which rely purely on the low-level visual features of stimuli to explain attentional guidance. That being said, it is worth noting that these models do not entirely deny the influence of semantic features. For example, recent updates of the FIT (Evans & Treisman, 2005; Treisman, 2006) do not rule out the possibility that some semantic features of objects, e.g., category membership, can be detected in the periphery of the visual field, and hence guide overt attention. Also, despite presenting a computational model of categorical search entirely relying on visual features of objects, (Zelinsky et al., 2013) do not rule out a possible role for semantic features in attentional guidance. Evidence of semantic relatedness on initial eye movements also directly speaks about the degree of object processing that may happen outside the fovea. It would indicate that high-level semantic information of objects over the visual field can be analysed in extra-foveal vision rapidly and to a degree sufficient to influence the planning and execution of the first saccades.

1.5 Extra-foveal processing of object semantics and semantic guidance of search in older adults

Semantic guidance of search requires observers to access object semantic information in extra-foveal vision which in turn relies on the processing of multiple visual features defining the objects, e.g., colour and shape, as postulated by models of rapid object recognition (Hummel, 2001; Mel, 1997; Mel & Fiser, 2000). From this, it follows that if the processing of visual features is degraded, access to objects' semantic information, as well as their ability to guide search, will be most likely impaired.

Healthy ageing is associated to a decline in visual processing abilities (Owsley, 2011), e.g., reduced visual acuity and contrast sensitivity (H. A. Greene & Madden, 1987; Owsley & Sloane, 1987), decreased colour discrimination (Cooper, Ward, Gowland, & McIntosh, 1991), degraded surface and contour detection (McKendrick, Weymouth, & Battista, 2010), and shape perception (Norman, Clayton, Shular, & Thompson, 2004), resulting from age-related changes to the visual system, from changes to the optical characteristics of the eyes (Scialfa, 2002), to deficits in the two main visual streams, the parvocellular and the magnocellular pathways (Elliott & Werner, 2010), to decreased activation of the visual sensory cortex (Huettel, Singerman, & McCarthy, 2001; Ward, Aitchison, Tawse, Simmers, & Shahani, 2015). Although there is evidence that age-related visual deficits hinder access to object semantic information, i.e., semantic category, in extra-foveal vision (Lenoble, Bordaberry, Rougier, Boucart, & Delord, 2013) whether and to what extent older adults rely on extra-foveal semantic processing to guide eye movements during search is still poorly understood.

Much of the research on visual search behaviour in older adults has focused on the age-related differences in the attentional guidance afforded by low-level visual features. This research shows that, when searching for a target, older adults are more likely to look at distractors visually similar to the target, than dissimilar to it, in arrays of abstract shapes (Dennis, Scialfa, & Ho, 2004) and real-world objects (Williams, Zacks, & Henderson, 2009). This indicates that, similarly to younger adults, older observers guide their search based on the knowledge of target's visual features (Madden, Gottlob, & Allen, 1999; Madden, Pierce, & Allen, 1996; Madden, Whiting, Cabeza, & Huettel, 2004; Whiting, Madden, Pierce, & Allen, 2005, for further related findings). Despite the similar search strategies, older adults display worse performances than younger adults when asked to search for a target object among distractors (see Zanto & Gazzaley, 2014, for a review). Older adults are less accurate and slower, i.e., response times, (Foster, Behrmann, & Stuss, 1995; Owsley, Burton-Danner, & Jackson, 2000; Watson, Maylor, & Manson, 2002) and take longer to locate the target object, i.e., more fixations (Porter, Tales, et al., 2010; Williams et al., 2009). These differences are more pronounced as the difficulty of the task increases, whereby ageing disproportionately slows search for conjunction compared to single-feature tasks, i.e., age x task interaction; for targets presented at peripheral than central regions of the visual field, i.e., age x eccentricity interaction; and as additional distractors are added to the visual context, i.e., age x set size interaction (Foster et al., 1995; Humphrey & Kramer, 1997; Plude & Doussard-Roosevelt, 1989; Potter, Grealy, Elliott, & Andrés, 2012; Watson, Maylor, & Bruce, 2005a, 2005b). Critically, these differences cannot be explained by a decrease in the speed to execute the cognitive operations relevant to the completion of the search task in older adults, i.e., generalised slowing of cognitive processing (Salthouse, 1996, 2012; but see F. W. Cornelissen & Kooijman, 2000; Hommel, Li, & Li, 2004; Muiños & Ballesteros, 2014; Muiños, Palmero, & Ballesteros, 2016; Porter et al., 2010, for contrasting results).

Little research has investigated the guidance of overt attention by object semantics in younger and older adults during search, providing contrasting conclusions. Boucart, Bubbico, Szaffarczyk, and Pasquier (2014) investigated the ability to detect a target object in naturalistic scenes in younger and healthy older adults, and Alzheimer's disease (AD) patients, using a saccadic choice task. Participants were presented for 1 second with two lateral (left/right) photographs of naturalistic scenes, one containing an animal (e.g., a mammal, a reptile, a bird, a fish) and the other containing various objects (e.g., means of transportation, flowers, fruits) and asked to move their eyes to the scene with the animal (See Figure 6 for an example of the experimental materials). The analysis on the accuracy of the first saccade showed that the first saccade landed on the region of interest (target animal) more often in younger than older adults, and more often in older adults than AD patients. The differences in attentional selection between younger and healthy older participants were interpreted in terms of an age-related deficit in the ability to categorize objects resulting from an impairment in processing diagnostic visual features, i.e., their global shape, in extra-foveal vision, associated to a dysfunction of the magnocellular pathway in old age (Bar, 2003; Lenoble et al., 2013). Therefore, in older adults, degraded visual inputs from the periphery of the visual field would hinder the extra-foveal processing of object semantic information, and thus semantic guidance of search.

Critically, in Boucart et al. (2014) only the accuracy of the first saccade was taken into account. In a recent study, Borges, Fernandes, and Coco (2020) examined the role of contextual expectations in age-related

Figure 6. Examples of pairs of scenes used in Boucart et al. (2014). At the beginning of the trials, a central white fixation cross was presented on a black background for 1000 ms. It was followed, after a gap of 200 ms, by a pair of pictures of naturalistic scenes, one containing an animal and one without animal, displayed for 3000 ms. The centre of each lateral picture was located 8° from the central fixation.

differences during visual search by analysing the latency to first fixation, z-scored to control for the confounding effect of general slowing. They found that both younger and older adults fixated objects (e.g., iron) inconsistent with the scene (e.g., restaurant) earlier than consistent objects (e.g., bread), with no difference between groups. This finding raises the possibility that older adults access extra-foveal semantic information as efficiently as younger adults to guide eye movements during search, but they might need more time to process stimuli in extra-foveal vision, thus explaining the age-related reduced semantic guidance on initial eye movements found in Boucart et al. (2014). I investigated this possibility in Chapter 3 (Experiment 3), where I employed the same experimental paradigm used in Experiments 1 and 2, and provided new evidence on the age-related differences in semantic guidance of overt attention during search and thus in the extra-foveal processing of object semantic information. Compared to Borges et al. (2020) who used naturalistic scenes and manipulated object-scene semantic consistency, my experiment focused on the guidance afforded by semantic relatedness, as well as visual saliency, in object arrays, thus eliminating potential confounding effects from scene contextual information. Also, I analysed both early, i.e., probability of first fixation, and overall, i.e., latency to first fixation, measures of attentional capture, which allowed me to examine age-related differences in the time-course of semantic relatedness effects on search.

1.6 Extra-foveal processing of object semantics and semantic guidance of search in Alzheimer's disease

Boucart et al. (2014) observed that AD patients were less accurate at directing the first saccade towards a categorically defined target, i.e., animal, in naturalistic scenes compared to healthy older adults. According to the authors, the lower accuracy resulted from deficits in the extra-foveal processing of the visual features of objects caused by a degradation of the magnocellular pathway, which in AD is greater than that observed in normal ageing (Gilmore & Whitehouse, 1995; Kergoat et al., 2002; Sartucci et al., 2010). In addition to deficits in visual processing (Cronin-Golomb, 1995; Rizzo, Anderson, Dawson, & Nawrot, 2000; Valenti, 2010), patients with AD also show impairments in semantic memory (Daum, Riesch, Sartori, & Birbaumer, 1996; Martin & Fedio, 1983; Mulatti, Calia, De Caro, & Della Sala, 2014), defined as conceptually organised knowledge not tied to specific episodes (Gold & Budson, 2008). From the early stages of the disease, AD patients exhibit deficits in word-finding abilities (Bandera, Della Sala, Laiacona, Luzzatti, & Spinnler, 1991; Spaan, Raaijmakers, & Jonker, 2003) and object naming (Holmes, Jane Fitch, & Ellis, 2006), and underperform on picture-to-word semantic association (Di Giacomo et al., 2012) and word-to-picture matching (Adlam, Bozeat, Arnold, Watson, & Hodges, 2006) tasks. In addition, compared to healthy controls, AD patients produce more semantic-superordinate errors when asked to generate names of objects belonging to a specific semantic category (see Salmon, Butters, & Chan, 1999, for a review) or they generate fewer words of a particular semantic category than words beginning with a particular letter (Phillips, Della Sala, & Trivelli, 1996), which suggests specific difficulties with semantic knowledge rather than generic disruptions linked to lexical retrieval (Monsch et al., 1994).

Although these findings have at times been interpreted as reflecting a breakdown of semantic knowledge in AD (Adlam et al., 2006; Hodges, Salmon, & Butters, 1992; Salmon et al., 1999), studies using tasks that can be performed more automatically and include a priming component have often reported evidence of preserved semantic abilities in AD patients. Semantic priming implies an automatic activation of information related to a processed stimulus, which results in faster responses when, for example, a stimulus is preceded by a semantically related cue compared to when the preceding cue is unrelated to the target stimulus (e.g., Gold & Budson, 2008). Studies that have used semantic priming in AD have reported performances comparable to age-matched control (Hernández, Costa, Juncadella, Sebastián-Gallés, & Reñé, 2008; Nakamura, Nakanishi, Hamanaka, Nakaaki, & Yoshida, 2000), or even more pronounced priming effects (Chertkow et al., 1994). Preserved semantic abilities in AD patients have also emerged with tasks not involving semantic priming but manipulating instead demands on selective attention. Tippett, Gendall, Farah, and Thompson-Schill (2004) tested patients and healthy age-matched individuals on a lexical fluency task, a comparison task and a verb generation task, and systematically varied the number of possible alternatives participants were faced with. In the verb generation task, for example, participants had to produce a verb related to a visually presented noun; in the high selection condition, the noun was associated with many appropriate responses (e.g., boat → row), whereas in the low selection condition with one or few responses (e.g., piano → play). The results of this study showed that, unlike controls, AD patients were disproportionately impaired in the high-selection conditions, even if these conditions were easier to complete. Similar results were also reported by Rich, Park, Dopkins, and Brandt (2002), who found that semantic judgements in AD patients in a sorting task were impaired when the retrieval context was unstructured (i.e., when the number of groups to sort items into was not specified), but performed normally under more structured conditions (i.e., when instead the number of groups was specified by the experimenter). The control of selective attention is known to be mediated by task requirements and declines in AD from the early stages (Baddeley, 2001). So, the evidence of preserved semantic abilities in AD may be linked to tasks that require a reduced attentional control and can be performed instead more automatically

(Ober, 2002; Perri et al., 2003). Therefore, AD may induce a selective impairment in the explicit access and intentional retrieval of semantic knowledge rather than its indiscriminate loss, and possibly this impairment stems from information processing deficits (Nebes, 1992; Ober, 2002; Rogers & Friedman, 2008), which would be consistent with the distinction between automatic and controlled memory processes (Jacoby, 1991; Moscovitch, 1992).

Additional differences in semantic processing relate to the type of stimuli used (e.g., verbal vs. non-verbal). Pictures are recalled better than words as we age (Ally et al., 2008); and their memorial advantage may be due to their dual coding in the semantic memory system (Ally, McKeever, Waring, & Budson, 2009). The picture superiority effect seems to be more pronounced in AD patients compared to healthy age-matched controls (Ally, Gold, & Budson, 2009; Rich et al., 2002), suggesting that pictorial stimuli may enable patients to access semantic information that is less accessible with lexical stimuli (Rich et al., 2002). In support of this, some patients show preserved information about the use of objects that they cannot name (Bartolo, Della Sala, & Cubelli, 2016). Impairment in lexical access and retrieval may thus have contributed to the finding of impaired performance on tasks of semantic memory that have used verbal stimuli (Cuetos, Arce, Martínez, & Ellis, 2017). Such lexical access requires an explicit top-down recollection of semantic knowledge, and it may precisely this mechanism to be particularly severed by AD. Semantic information may still be accessed to a certain degree by AD patients when processed in a more implicit and automatic way. One way to investigate whether AD patients preserve a more automatic processing of semantic information is by looking at their eye-movement responses, which can be taken as implicit measures of memory processes even when explicit conscious recollection seems to fail (Hannula et al., 2010). For instance, in visual search tasks with complex scenes, target detection is affected by previous knowledge of the specific contexts in which objects are more likely to occur (Castelhano & Heaven, 2011; Castelhano & Henderson, 2007; Malcolm & Henderson, 2010; Neider & Zelinsky, 2006), which indicates that semantic knowledge modulates how we extract visual information. Moreover, eye movements on a target object precede its explicit identification by as many as 25 fixations (Holm, Eriksson, & Andersson, 2008), and longer fixations are observed when a target object embedded into a scene is changed, even when such a change is not consciously detected by the participants (Hollingworth, Williams, & Henderson, 2001). When looking at AD patients searching for a target embedded in arrays of other stand-alone distractor objects, they display longer fixations, make more errors and are overall slower than healthy age-matched individuals (Porter, Leonards, et al., 2010; Rösler et al., 2000; Tales et al., 2002). Furthermore, AD patients display a greater number of peripheral fixations compared to younger and older healthy participants, which may additionally suggest a reduction in their useful field of view (Rösler, Mapstone, Hays-Wicklund, Gitelman, & Weintraub, 2005). However, it still unclear whether object semantic information can be processed enough by AD patients to modulate their eye-movement responses, and hence show that this ability is preserved to a certain degree. This is the aim of Experiment 4 (Chapter 4) which examined the eye-movement behaviour of AD patients and healthy age-matched controls on the same visual search task used in previous experiments and provided new evidence on the nature of the semantic impairment in patients with AD.

1.7 The interplay of saliency and semantic features in the guidance of overt attention during memorization

In the first four experiments of this thesis, I monitored the eye movements of participants inspecting object arrays during a visual search task and examined the influence of high-level semantic information, and low-level visual saliency, on the allocation of overt attention. It is well known that the type of task performed strongly influences the contribution of bottom-up, stimulus-driven, and top-down, knowledge-based information to selecting regions of a visual context deemed as interesting and worth of attention (Coco & Keller, 2014; Einhäuser et al., 2008; Foulsham & Underwood, 2007; Underwood & Foulsham, 2006; Underwood et al., 2006). In visual search, the relevant object to look for is set by the task, i.e., target object, and overt attention is mostly guided by top-down knowledge related to it (Castelhano & Heaven, 2011; Malcolm & Henderson, 2009, 2010). Instead, in other tasks, such as naming and memorization, no target object is specified. In these tasks, all objects are equally task-relevant and, as a result, fixations should be more guided based on bottom-up information, while the effects of top-down knowledge should be less pronounced (Foulsham & Underwood, 2007). Several studies show that visual saliency and semantic information interact in guiding visual attention, with visual saliency being prioritised (Coco et al., 2014; Underwood & Foulsham, 2006). For example, Underwood and Foulsham (2006) asked participants to freely inspect naturalistic scenes which contained objects whose saliency and contextual congruency were manipulated, in preparation for a memory task. Salient objects were looked at earlier than non-salient objects, independently of their congruency with the scene. Objects inconsistent with the scene were fixated earlier than consistent objects, only when non-salient. Critically, these findings contrast with the results of other studies reporting that semantic information has instead a predominant influence over visual saliency (Nyström & Holmqvist, 2008; Spotorno & Tatler, 2017; Underwood et al., 2008). For instance, Nyström and Holmqvist (2008) had participants freely inspecting naturalistic scenes, and showed that the degree to which visual saliency influenced fixation location strongly depended on the semantic content of the scene. Attention was allocated to high-salient regions of the scene only for scenes with neutral semantic content (e.g., a picture of a brick wall); whereas in scenes containing semantic relevant regions (e.g., faces), overt attention was preferentially directed towards them, even if they were low in saliency.

Understanding the interplay between low-level saliency and high-level semantic information in guiding visual attention has important implications for refining theories of visual cognition which posit a predominant role for either bottom-up (Itti & Koch, 2000; Parkhurst et al., 2002; Walther & Koch, 2006) or top-down information (e.g., Henderson, Malcolm, & Schandl, 2009) in guiding attention. It would also contribute to extending our comprehension of the functioning of other cognitive processes, such as memory. A great deal of research provides strong evidence of a link between attention selection processes and memory (Awh, Vogel, & Oh, 2005; Chun & Turk-Browne, 2007; Gazzaley & Nobre, 2012). Several studies show that fixated objects are better remembered than non-fixated objects (Botta, Santangelo, Raffone, Lupiáñez, & Belardinelli, 2010; Clarke, Coco, & Keller, 2013; Hollingworth & Henderson, 2002; B. K. Schmidt, Vogel, Woodman, & Luck, 2002). Sustained attention on objects, i.e., number of fixations and total fixation durations, also influence their memorization, whereby objects fixated more often and for longer have a greater probability to be verbally recalled (Clarke et al., 2013). Moreover, memory performance is impaired when attention is divided between multiple tasks during encoding (Craik, Govoni, Naveh-Benjamin, & Anderson, 1996). Given that overt attention plays a strong role in determining whether an object will be remembered or not, and that it is preferentially directed towards salient (Coco et al., 2014; Elazary & Itti, 2008; Foulsham & Underwood, 2007; Masciocchi et al., 2009; Parkhurst et al., 2002; Underwood & Foulsham, 2006) and semantically inconsistent objects (Bonitz & Gordon, 2008; Brockmole & Henderson, 2008; Cornelissen & Võ, 2017; LaPointe & Milliken, 2016; Underwood & Foulsham, 2006; Underwood et al., 2008) during scene viewing, one would expect these objects to have an advantage to be encoded in memory and then correctly remembered, compared to non-salient and consistent objects (Bundesen, 1990; Bundesen, Habekost, & Kyllingsbæk, 2005, 2011; see also Pedale & Santangelo, 2015; Spotorno & Tatler, 2017; Stirk & Underwood, 2007, for examples of memory studies which speculatively support this hypothesis, but as they do not examine eye-movement behaviour, they do not directly test it). Studies investigating the relationship between low-level saliency and memory consistently found that salient objects are indeed remembered more often than non-salient ones (Fine & Minnery, 2009; Pedale & Santangelo, 2015; Santangelo & Macaluso, 2013). Critically, this relationship does not necessarily depend on attentional prioritisation of salient objects. For example, Fine and Minnery (2009) showed that salient objects are better remembered, even though they are fixated as early as and for as long as non-salient objects. They interpreted these findings by suggesting that saliency influences memory, and it can do it covertly and/or pre-attentively. As for the effects of high-level semantic information on memory, vision research frequently reports that objects consistent with a scene are more easily identified (Davenport, 2007; Davenport & Potter, 2004) and remembered (Silva, Groeger, & Bradshaw, 2006; Spotorno, Tatler, & Faure, 2013) than inconsistent objects. This represents a paradoxical finding, given the extensive evidence supporting an attentional prioritisation of inconsistent objects. Different factors, other than the differential allocation of overt attention, must be thus considered, i.e., contextual facilitation (Davenport, 2007; Hollingworth & Henderson, 1999; Silva et al., 2006). The early identification of the context of the scene might enhance the perceptual processing of consistent objects, thus facilitating their access to memory (in this case the memory advantage for consistent objects would arise at encoding), or might be used by observers to make an informed guessed about the consistent objects presented (in this case the advantage would arise at retrieval). Interestingly, even when participants show an advantage for remembering inconsistent objects, this cannot be simply accounted for a preferential allocation of attention towards them, as demonstrated by Hollingworth and Henderson (2000) in a change detection task where stimuli presentation was so brief that eye movements could not take place. According to the authors, it is possible that attention was drawn covertly and/or pre-attentively to inconsistent objects (Gordon, 2004), thus aiding their memorization.

The research literature on naturalistic scenes been examining the influence of high-level semantic information, and low-level visual saliency, on eye movements, but remains inconclusive about how they interact in guiding visual attention. Also, it is still unclear whether the saliency and semantic features of objects influence their memorization by affecting eye movements.

In Experiment 5 of the current thesis, I addressed these issues by adapting the experimental paradigm used for the visual search task to a memory task. That is, young participants were presented with object arrays containing a critical object plus 2, 4 or 6 additional semantically homogenous distractor objects. The critical object was either salient or non-salient, and either semantically related or unrelated to the distractors. Participants were asked to freely inspect the object arrays and to memorize as many objects as possible in preparation for a verbal recall memory task, which occurred immediately after inspection. I analysed the probability of recalling the critical object and expected to replicate results from previous studies which found that salient and semantically related objects are more easily recalled than non-salient and semantically unrelated objects (Guerin & Miller, 2008; Pedale & Santangelo, 2015; Poirier, Saint-Aubin, Mair, Tehan, & Tolan, 2015; Saint-Aubin, Ouellette, & Poirier, 2005). Moreover, I analysed both eye-movement measures of attentional capture and fixation processing on the critical object to examine the interplay of semantic relatedness and visual saliency on eye-movement behaviour, and see whether the memory advantage for salient and semantically related objects could be explained by overt attentional effects, e.g., longer fixations on these objects. A similar experimental paradigm of free recall with object arrays was used, for the first time, only recently by Suzin, Ravona-Springer, Ash, Davelaar, and Usher (2019). They monitored the eye movements of younger and older adults while looking at object arrays, in preparation for later verbal recall. The arrays consisted of either nine semantically unrelated objects or objects selected from three semantically related categories, with three objects from each category. Both younger and older adults recalled more objects when they were related than unrelated, with this difference being more pronounced for the younger than the older group. They also observed that the sequence of eye movements of the younger, but not the older adults, showed a semantic clustering strategy, i.e., they progressively scanned the arrays based on the semantic relationship of the objects. The grouping of semantically related objects during inspection might have enhanced their encoding in memory, i.e., memorising an object is easier when a semantically related object has just been committed to memory (Cadar, Usher, & Davelaar, 2018; Glanzer, 1969), thus explaining the age-related differences in memory performances. Despite smaller, the effect of semantic relatedness was still significant in older adults, possibly due to a retrieval benefit, i.e., one object helps recall a semantically related object through semantic priming, which can be preserved in ageing (Laver & Burke, 1993; Mehta & Jerger, 2014).

Compared to Suzin et al. (2019), Experiment 5 manipulated the visual saliency of the objects along with their semantic relatedness. In particular, the influence of visual saliency on overt attention could be stronger in older than younger adults as suggested by previous studies on age-related differences in attentional selection by bottom-up information (Tsvetanov, Mevorach, Allen, & Humphreys, 2013), and given the lack of top-down semantic guidance in older age reported by Suzin et al. (2019). This possibility is further investigated in Experiment 6, where I used the same experimental paradigm as Experiment 5 to compare the effects of visual saliency and semantic relatedness information on visual attention and memory performances of younger and older adults.

2 Methodology

2.1 Introduction

In this chapter, I present the common methods and statistical analyses used throughout the experiments of this thesis. In section 2.2, I begin by presenting the experimental designs of each experiment. In section 2.3 and 2.4, I describe the stimulus materials and the procedures for their norming. Section 2.5 shows how I implemented the critical experimental manipulations of visual saliency and semantic relatedness, whereas section 2.6 illustrates the method I used to quantify visual similarity and, thus, check for its confounding effects. Section 2.7 gives information about the apparatus used for conducting the experiments. In section 2.8, I list the dependent variables examined across the experiments. In section 2.9, I motivate the choice of linear and generalized linear mixed-effects models (G/LMM) for data analysis and describe the procedures adopted for model selection, and for reporting and visualising data. Finally, section 2.10 provides information about the general criteria used for the recruitment of participants and the ethics statement.

2.2 Designs

For Experiments 1 and 2, which had young adults performing a visual search task, and Experiment 5, where further young adults performed a memory task, I used a 2x2x3 mixed factorial design with two-within participant variables, Semantic Relatedness (unrelated, related) and Visual

Saliency (non-salient, salient) and one between-participants variable, Set Size (3, 5, 7). I created the experimental arrays for the three different set size conditions starting with the three-object arrays (e.g., car - truck - motorcycle) and then adding two more objects (e.g., helicopter - bus) to obtain the five-object arrays, and two more (e.g., boat - train) for the seven-object arrays (See Figure 7 for an example of the three types of arrays). Then, I manipulated set size between-participants, to avoid repeating the same visual objects across trials and increase the number of observations for each set size.

Experiments 3 and 4 used five-object arrays only to compare search performances of younger and healthy older adults, and AD patients and age-matched healthy control, respectively. For both these experiments, a 2x2x2x2 mixed factorial design was used with Semantic Relatedness (unrelated, related), Visual Saliency (non-salient, salient), and Target (absent, present) as within-participants variables, and Group (younger, older in Experiment 3; control, AD in Experiment 4) as between-participants variable.

For Experiment 6, which used five-object arrays only to examine age-related differences in a memory task, I used a 2x2x2 mixed factorial design with Semantic Relatedness (unrelated, related) and Visual Saliency (non-salient, salient) as within-participants variables, and Group (younger, older) as between-participants variable.

Experiments 3, 4, and 6 did not manipulate the set size of the arrays because of the difficulty to recruit healthy older and AD participants.

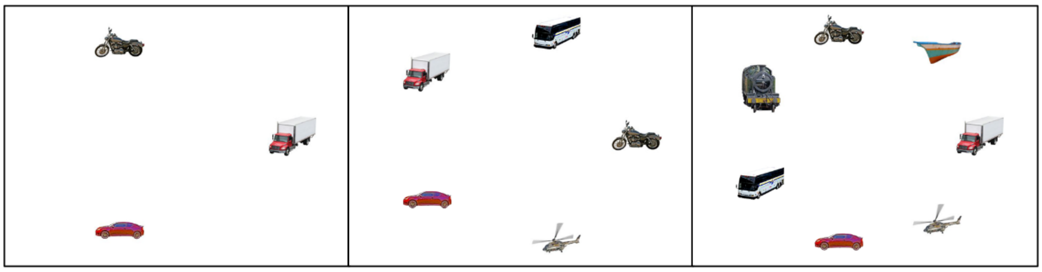


Figure 7. Example of an object array of different sizes: three-object array (left panel), five-object array (central panel), seven-object array (right panel).

2.3 Object pictures and norms

The visual contexts used for the experiments were arrays of pictures of real-world objects taken from the Bank of Standardized Stimuli (BOSS) database (Brodeur, Dionne-Dostie, Montreuil, & Lepage, 2010; Brodeur, Guérard, & Bouras, 2014). The BOSS database contains a total of 1,468 high-quality pictures of real-world objects, sized 2000 x 2000 pixels, which have been normed along different variables, including naming and semantic category agreement, on a large sample of native English speakers. For the naming norms, subjects were presented with one object at the time and asked to identify them by writing the first name that came to mind. In case they could not recognize the object, they were instructed to write “DKO” (Do not Know Object). If they could recognize the object but they did not know its name, they wrote “DKN” (Do not Know Name), whereas they wrote “TOT” (Tip Of the Tongue) in case they could not retrieve the name of the object at that moment. For the semantic category norms, subjects were presented with a list of semantic category labels and asked to determine the one to which the object belonged. Then, for each object, the percentage of subjects using each name was computed to extract the modal name and the corresponding percentage of agreement. The modal name consisted of the name given by the highest percentage of participants for a given object after the exclusion of the DKO, DKN and TOT responses. This percentage corresponded to the modal name agreement which indicated to what extent participants agreed to use the modal name to identify the object. The same procedure was used to obtain the modal category (i.e., the most selected semantic category label for a given object) and the modal category agreement (i.e., the corresponding percentage of agreement).

I selected a total of 387 object pictures from the BOSS database. In selecting the object pictures, I excluded those with either a DKO, DKN, or TOT score over 25%; those with a modal name agreement below 45%; and/or those which could not be intuitively classified within any of the 20 semantic category labels used in the current thesis; see Table 1 for the list of semantic category labels: six category labels were taken from the Battig and Montague's (1969) category norms, two from the Brodeur et al.'s (2014) normative study, and an additional 12 new category labels were originated here.

The 387 object pictures were then scaled from their original size (2000 x 2000 pixels) to 150 x 150 pixels, and pre-tested through an online, computer-based, survey administered by using the Online Surveys tool. The survey, which included a naming and a semantic categorization task, had two aims. First, I needed to make sure that, at a lower format, object pictures could be recognized and named correctly. Also, as the semantic categories used here were different from those of the BOSS database, a new

Table 1

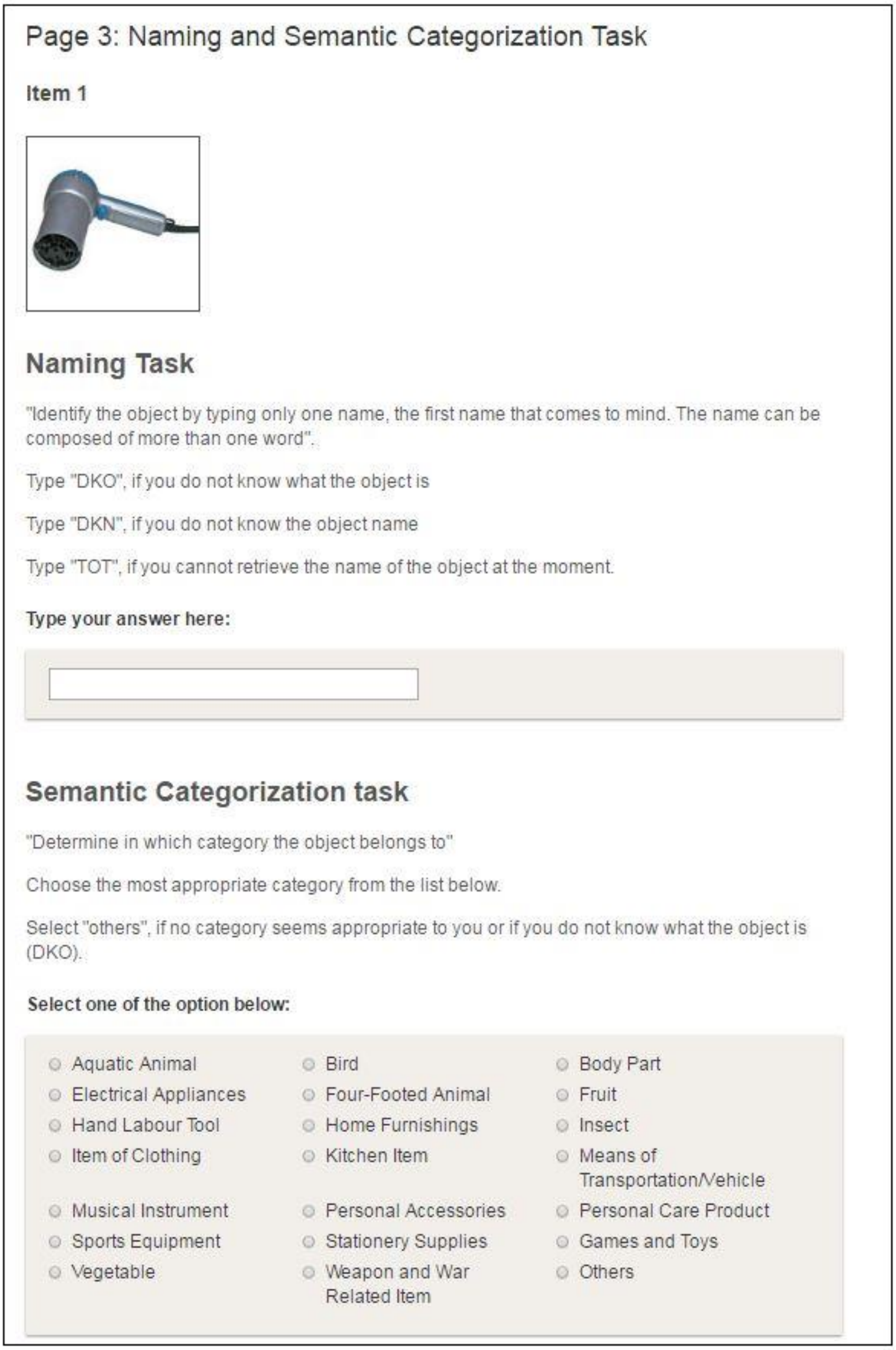
The 20 Semantic Category Labels Grouped by Source

No.	Semantic category label	Source
1	Four-footed animal	
2	Fruit	
3	Musical instrument	Battig and Montague (1969)
4	Vegetable	
5	Insect	
6	Bird	
7	Weapon and war-related item	Brodeur et al. (2014)
8	Body part	
9	Aquatic animal	
10	Electrical appliances	
11	Games and toys	
12	Home furnishings	
13	Personal accessories	Current thesis
14	Personal care product	
15	Hand labour tool	
16	Item of clothing	
17	Kitchen item	
18	Means of transportation/Vehicle	
19	Sport equipment	
20	Stationery supplies	

classification of objects was needed.

Ten participants (3 women), ranging between 23 and 63 years of age (M = 31.40, SD = 12.85) and 11 and 18 years of schooling (M = 16.6, SD = 2.72), took part in the survey. All reported being native English speakers, with English (either British or American) as first language. The survey was divided into three parts. For each part of the survey, a random sequence of 129 object pictures was generated (i.e., 129 * 3) and presented to the participants. The order of presentation did not differ across participants. In the survey, participants were presented with one object at the time and asked to name and categorize them. For both the naming and the semantic categorization task, instructions were almost identical to those used in the BOSS normative studies (Brodeur et al., 2010, 2014) and were given both prior to the beginning of the survey and upon presentation of each object. In the naming task, participants were asked to identify each object by typing on their keyboard either the first name that came to mind, or “DKO”, “DKN”, or “TOT”, where necessary. In the semantic categorization task, they were instructed to determine the semantic category the object belonged to by making a selection across 20 given categories and an “Others” choice. The “Others” choice had to be picked either if no category seemed to be appropriate or in case a DKO response had been previously provided in the naming task (See Figure 8 for a trial example). For each object, I then derived the modal name, modal category, and the corresponding percentages of agreement, using identical procedures to those in the BOSS database.

Of the 387 objects initially submitted to the online survey, 47 were excluded either because they had a DKO, DKN, or TOT score over 20%; their modal name was incorrect or, when correct, had a percentage of agreement of less than 20%; they were not assigned to any specific category (“Others” as modal category); or because their modal category agreement was below 50%. Interestingly, 90.88% of the remaining 340 objects had the same modal name in both the online survey and the BOSS normative studies



Page 3: Naming and Semantic Categorization Task

Item 1

Naming Task

"Identify the object by typing only one name, the first name that comes to mind. The name can be composed of more than one word".

Type "DKO", if you do not know what the object is

Type "DKN", if you do not know the object name

Type "TOT", if you cannot retrieve the name of the object at the moment.

Type your answer here:

Semantic Categorization task

"Determine in which category the object belongs to"

Choose the most appropriate category from the list below.

Select "others", if no category seems appropriate to you or if you do not know what the object is (DKO).

Select one of the option below:

Aquatic Animal	Bird	Body Part
Electrical Appliances	Four-Footed Animal	Fruit
Hand Labour Tool	Home Furnishings	Insect
Item of Clothing	Kitchen Item	Means of Transportation/Vehicle
Musical Instrument	Personal Accessories	Personal Care Product
Sports Equipment	Stationery Supplies	Games and Toys
Vegetable	Weapon and War Related Item	Others

Figure 8. Online survey trial example.

(Brodeur et al., 2010, 2014). Hence, when the modal name differed (e.g., “phone” and “motorbike” in the online survey vs. “telephone” and “motorcycle” in the BOSS norms), I decided to label the objects by using the BOSS modal names. This allowed me to apply two additional selection criteria to the stimulus set: (1) I excluded objects with either a BOSS modal name agreement below 50%, or a DKO, DKN or TOT score over 20% (2) in case two or more objects were given the same modal name and modal category, I included in the stimulus set only the object with the highest BOSS modal name agreement. Eventually, the stimulus set resulted in a total of 289 object pictures, all accurately nameable and univocally classifiable into the 20 semantic categories (see Table 2 for the descriptive statistics for the variables examined on the stimulus set).

The participants recruited for Experiments 1, 2, 3, 5, and 6 were native English speakers, whereas the AD patients and age-matched healthy controls who took part in Experiment 4 were native Italian speakers. I derived the Italian modal names for the object pictures used in this experiment through an online survey administered to ten participants (4 women), all native Italian speakers, ranging between 23 and 32 years of age (M = 27.4, SD = 3.06) and 13 and 18 years of schooling (M = 16.9, SD = 1.52). The survey was identical to the one conducted on native English speakers, with the exception that the instructions were in Italian and that it included only the naming task. For each object, I computed the modal name and modal name agreement, which was never below 20% (min = 33, max = 100, M = 89.64, SD = 16.78).

Table 2

Minimum, Maximum, Mean, and Standard Deviation (percentages) for the Stimulus Set

Variables	Minimum	Maximum	Mean	SD
Modal name agreement	30	100	86.97	17.12
DKO	0	20	1.45	4.16
DKN	0	20	0.66	2.87
TOT	0	20	0.59	2.76
Modal category agreement	50	100	87.92	15.72

Note. The modal name agreement was 30% for one stimulus only, i.e., “sport bag”, which participants named using a wide range of synonyms: “bag” (which was the modal name for this stimulus), “holdall” (20%), “duffle bag” (20%), “rucksack” (20%), “satchel” (10%).

2.4 Object arrays

The object arrays consisted of pictures of real-world objects, sized 150 x 150 pixels, placed on a uniform white background and arranged on an imaginary circle such that the midpoint of each object was equidistant from the centre of the array (corresponding to the starting fixation point) and the two adjacent objects’ midpoints.

For each experiment, and within each array set size in Experiment 1, 2, and 5, no object picture was presented more than once to avoid any uncontrolled effect that may derive from repeated exposures to the same stimulus.

Each experimental array contained a critical object whose position was counterbalanced by rotating it in different locations of the array, in order to account for potential directional biases. The critical object was the one for which I manipulated the visual saliency and its semantic relatedness with the other objects in the arrays, i.e., distractors. The critical objects were selected prior to data collection and data analysis, especially taking into account the easiness to implement the visual saliency manipulation.

2.5 Visual saliency and semantic relatedness

The visual saliency of the critical object was manipulated by changing its brightness/contrast and hue/saturation with GIMP (Version 2.8.2). They were adjusted so that the critical object was among the least and the most salient regions of the array in the non-salient and salient condition, respectively. The efficiency of the saliency manipulation was verified by using the Walther and Koch's Matlab Saliency Toolbox (2006). First, a saliency map of the object array is computed. The Walther and Koch's algorithm uses the map to identify saliency peaks on the regions of the array where objects are located based on variation in orientation, intensity, and colour. Then, a rank is assigned to each saliency peak, with rank 1 for the array region containing the most salient object. These ranks are then used to simulate in what order the objects on the array should be inspected based on their visual saliency (See Figure 9 for an example of the Walther and Koch's Matlab Saliency Toolbox output). A Wilcoxon signed-rank test on the rank order of saliency peaks confirmed that the critical object was visually more conspicuous in the salient than in the non-salient condition (for Experiments 1, 2, and 5: *Mdn* = 1 vs. 4, $p < .001$, *z-coefficient* = -12.20; for Experiments 3, 4, and 6: *Mdn* = 1 vs. 4, $p < .001$, *z-coefficient* = -7.98).

The semantic relatedness manipulation was implemented by constructing object arrays with all objects belonging to the same semantic

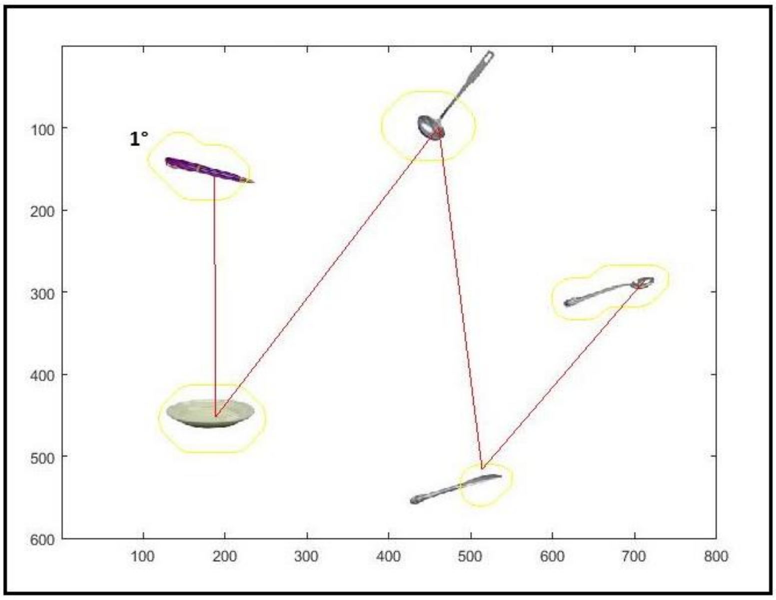


Figure 9. Example of graphical output from the Walther and Koch's Matlab Saliency Toolbox (2006). The region of the array containing the critical object, i.e., the pen, is ranked as the most salient, and simulated to be the first inspected by visual attention, followed by the plate, the ladle, the knife, and the spoon.

category (related), or, all distractors of the same semantic category but the critical object of a different one (unrelated). I validated the semantic manipulation by using Latent Semantic Analysis (LSA, Landauer & Dumais, 1997; Landauer, Foltz, & Laham, 1998), which is a distributional statistical model trained on co-occurrences of words in a text corpus to derive a quantitative measure of their semantic similarity. It is based on the idea that the more words appear in similar linguistic contexts, the more they are semantically similar among each other. A high-dimensional "semantic space" is established from a text corpus and words can be represented as vectors in this space. These vector representations map the location of the words in the high-dimensional space with similar vectors indicating similar locations and thus, similar meanings. The proximity of two words can be calculated as the cosine value of the angle between the two corresponding vectors in the semantic space. The higher the cosine value, the stronger the semantic similarity among words. Importantly, as semantic relationships are generated at a conceptual level, LSA can be used for deriving a measure of semantic similarity among object pictures, provided that they had been verbally labelled (see Hwang, Wang, and Pomplun, 2011; for an example of implementation of LSA in the context of visual search).

For the current thesis, I used the LSA trained on co-occurrences of words implemented by Hoffman, Lambon Ralph, and Rogers (2013) on labels of objects as normed by Brodeur et al. (2010, 2014). LSA returns a score that indicates the strength of semantic similarity between pairs of objects (between 0, the lowest, and 1, the highest). For each experimental array, I computed the mean semantic similarity score of the critical object with every other distractor. A t-test confirmed that the semantic similarity between the critical object and all other distractors was significantly higher in the semantically related than unrelated condition (for Experiments 1, 2, and 5: M = .51, SD = .23 vs. M = .01, SD = .09; $t(95)$ = 19.80, p< .001, *Cohen's d* = 2.02; for Experiments 3, 4, and 6: M = .44, SD = .24 vs. M = .01, SD = .08; $t(39)$ = 10.52, p< .001, *Cohen's d* = 1.66).

2.6 Visual similarity

Visual objects belonging to the same semantic category are likely to share visual features (e.g., colour, shape), and this may make the critical object visually more similar to the distractors when semantically related than when unrelated to them (Hwang et al., 2011). In order to examine this scenario, I used the Bank of Local Analyzer Responses (BOLAR) method (Zelinsky, 2003), which provides a quantitative measure of the visual similarity between pairs of visual stimuli, e.g., object pictures. The BOLAR represents an object picture as a vector of responses derived from a collection of filters that decompose each picture into multiple feature dimensions (colour, orientation, and size). The visual similarity between two pictures is computed as the linear difference between their vectors, i.e., difference vector. Subsequently, the difference vector is reduced to a single score by calculating the sum of squared responses from the difference vector and then taking the square root of that outcome. Finally, these scores are normalized relative to the entire set of pictures submitted to the analysis by dividing each score by the largest difference found in the set and subtracting the scores from 1. The resulting scores range from 0 to 1, with higher values indicating greater visual similarity; see also Ko, Duda, Hussey, and Ally, (2013), and Ko, Duda, Hussey, Mason, and Ally (2014) for examples of similar research using the same method.

For each experimental array, I computed the mean visual similarity score of the critical object with every other distractor. A t-test showed that the critical object was visually more similar to the semantically related than unrelated distractors (for Experiments 1, 2, and 5: M = .52, SD = .14 vs. M = .49, SD = .14; $t(95)$ = 3.36, p= .001, *Cohen's* d = .34 ; for Experiments 3, 4, and 6: M = .52, SD = .13 vs. M = .49, SD = .13; $t(39)$ = 2.39, p= .02, *Cohen's* d = .38). To control for the effects of visual similarity, I included it in the models as a quasi-experimental predictor, i.e., Visual Similarity, which was obtained by splitting the experimental items into two groups (dissimilar, similar) based on the median score obtained with the BOLAR (for Experiments 1, 2, and 5: *Mdn* = .50; for Experiments 3, 4, and 6: *Mdn* = .52).

2.7 Apparatus

For Experiments 1, 2, 3, 5, and 6, visual stimuli were displayed on a 21-inch ViewSonic G225f-CRT monitor with a refresh rate of 60 Hz using an Asus GeForce GT730 graphics card. Eye movements were monitored using an EyeLink 1000 (SR Research) at a sampling rate of 1000 Hz and a spatial resolution of 0.01° of visual angle. Although viewing was binocular, only the dominant eye was tracked (assessed through the parallax test). A forehead and chin rests were used to keep participants' viewing position stable. Stimulus presentation and data acquisition were implemented on Experiment Builder (SR Research, Version 1.10.1630).

For Experiment 4, visual stimuli were displayed on a 19-inch Sony SDM E96D monitor, and eye movements were recorded using a Gazepoint GP3 HD 150 eye-tracker (150 Hz sampling rate). Viewing was binocular, and both eyes were tracked. A forehead and chin rests were used to stabilise the participants' viewing position. The experiment was built using OpenSesame (Version 3.1.9; Mathôt, Schreij, & Theeuwes, 2012) and the PyGaze Python plug-in (Dalmaijer, Mathôt, & Van der Stigchel, 2014) was used to acquire the eye-movement data.

2.8 Dependent Variables

Both the visual search tasks (Experiments 1 to 4) and the memory tasks (Experiments 5 and 6) comprised performance measures and eye-movement measures on the critical object as dependent variables.

For the visual search tasks, the performance measures considered were the response accuracy, a binary variable indicating the accuracy of the yes/no target identification response (0 = “Incorrect”; 1 = “Correct”); and the response time, which is the time taken by the participants to provide the yes/no target identification response after the onset of the object array. The response times were log-transformed (natural log-scale) to reduce the positive skew of their distribution. On the eye-movement responses, I computed: (a) the probability of immediate fixation, which is a binomial variable indicating whether the first fixation after the onset of the object array (excluding the initial fixation to the centre of the screen) landed on the critical object (0 = “No”; 1 = “Yes”); (b) the search latency, which is the time between the onset of the array and the first fixation to the critical object; (c) the first-gaze duration, which is the sum of all consecutive fixations the critical object received for the first time before fixating elsewhere; and (d) the dwell time, that is the ratio between the total fixation duration on the critical object and the sum of the duration of all fixations occurring during the whole trial. It indicates the proportion of time spent looking at the critical object during the whole trial. The probability of immediate fixation and the search latency reflect the strength of an object to attract overt attention from the extra-foveal region of the visual field. The first-gaze duration and the dwell time instead are measures of foveal processing and reflect the difficulty of processing an object once attended.

For the memory tasks, the performance measure considered was the recollection probability, a binary variable indicating whether the critical object was recalled or not (0 = “No; 1 = “Yes”), which measures the ability of an object to be encoded and stored in memory. On the eye-movement responses, I computed: (a) the fixation probability, a binomial variable indicating whether the critical object was fixated, or not, during the whole trial (0 = “No”; 1 = “Yes”); (b) the time to first fixation to the critical object, which corresponds to the search latency in the visual search tasks; and (c) the total fixation duration, which is the sum of the duration of all fixations on the critical object during the whole trial, and represents a measure of foveal processing.

For Experiments 3 and 6, where I analysed the effects of ageing, i.e., younger adult and healthy older groups, on search and memorization, respectively; and for Experiment 4, where I compared the performances of AD patient and age-matched healthy control groups in a visual search task, the time-dependent measures, i.e., response time, search latency/time to first fixation, and total fixation duration, were z-scored to account for the general slowing of cognitive processes associated to healthy ageing and AD (Faust, Balota, Spieler, & Ferraro, 1999) The z-score transformation would ensure the means of these measures to be similar among groups (i.e., no significant main effect of group), with any true difference between them emerging in the interaction between the group variable and the other variables examined in my experiments (e.g., semantic relatedness).

2.9 Data analysis

For Experiments 1, 2, 3, 5, and 6, raw gaze data were parsed into fixations and saccades using SR Research Data Viewer using the standard settings (i.e., velocity and acceleration thresholds of 30°/s and 9,500°/s2, respectively). For Experiment 4, fixations and saccade events were extracted from the raw eye-movement samples with the I2MC algorithm, which is particularly suitable for noisy and low-frequency data (Hessels, Niehorster, Kemner, & Hooge, 2017), using Matlab (R2016b). I annotated each experimental array by drawing bounding boxes around each visual object (i.e., the critical object and all other distractor objects) using LabelMe (Russell, Torralba, Murphy, & Freeman, 2008); refer to Supplemental Materials A to visualize the miniatures of all the experimental arrays, with the critical object surrounded by the bounding box, used in this thesis. Then, I assigned all fixation coordinates to such areas of interest.

I used linear and generalized linear mixed-effects models (G/LMM), as implemented by the lme4 package (Bates, Machler, Bolker, & Walker, 2015) in R (version 3.2.5), to analyse the data. There are two main reasons why I preferred linear and generalized linear mixed-effect models over the analysis of variance (ANOVA) for statistical inference. First, their ability to capture the variance attributed to more than one random variable, e.g., participants and items, concurrently within a single analysis (Judd, Westfall, & Kenny, 2017; Locker, Huffman, & Bovaird, 2007). Second, these models guarantee better preservation of statistical power in the presence of missing data (e.g., Baayen, Davidson, & Bates, 2008), which is often the case in eye-tracking studies, especially with elderly and pathological populations.

I used a forward best-path model selection technique to define the fixed (e.g., semantic relatedness, visual saliency) and the random effect (i.e., participant and item) structures of the models (see Barr, Levy, Scheepers, & Tily, 2013; Coco et al., 2014, for examples of this approach). First, I centred the fixed effects to be included in the models to reduce collinearity, i.e., Semantic Relatedness (unrelated = -.5, related = .5), Visual Saliency (non-salient = -.5, salient = .5), Target (absent = -.5, present = .5; for Experiments 3 and 4, only), Set Size (3, 5, 7; for Experiments 1, 2, and 5, only), where I used set size 3 as the reference level (3 vs. 5: 3 = -.5, 5 = .5; and 3 vs. 7: 3 = -.5, 7 = .5), Visual Similarity (dissimilar = -.5, similar = .5), and Group (younger = -.5, older = .5, for Experiments 3 and 6, only; and control = -.5, AD = .5, for Experiment 4, only). Then, I started with a basic model including participant and item as random intercepts (i.e., `DV ~ (1 | participant) + (1 | item)` in Wilkinson notation). Then, I added each fixed effect to this basic model, individually (e.g., `DV ~ semantic relatedness + (1 | participant) + (1 | item)`). Such model was then compared with the same model but now including either correlated (e.g., `DV ~ semantic relatedness + (1 + semantic relatedness | participant) + (1 | item)`) or uncorrelated random slopes (e.g., `DV ~ semantic relatedness + (1 | participant) + (1 | item) + (0 + semantic relatedness | participant)`). I then compared the three models on their log-likelihood using chi-square tests (i.e., χ^2). I retained the model with the strongest fit (lowest p-value with a threshold of $p < 0.09$ to include marginally significant results). I repeated the same procedure independently for each fixed effect, and ordered their inclusion based on their log-likelihood significant fit (e.g., if semantic relatedness resulted in a better fit than visual saliency, I included semantic relatedness before visual saliency), whereas non-significant fixed effects were dropped. Finally, I added interactions, but only for those fixed effects that were retained during model selection. The same model selection procedure was implemented for all the experiments, with the exception that for Experiments 3, 4, 6, where the performances of different groups of participants were compared (younger adults, older adults, and AD patients), the fixed effect of group was retained during model selection even when non-significant, in order to test for its potential interactions with the other variables of interest.

The results of the analyses conducted for each experiment of the thesis are reported in tables listing coefficients, standard errors, t-values (LMM), and z-values (GLMM) of those predictors that were retained in the final models. I also report their p-values based on Satterthwaite approximation for denominator degrees of freedom computed using the lmerTest R package (Kuznetsova, Brockhoff, & Christensen, 2017), whereas p-values in GLMM are based on asymptotic Wald tests. Predictors that were not retained during model selection, because they did not significantly improve the model fit, are not listed in the tables, nor they are plotted in the figures (see also the figures in Supplemental Materials B, where both significant and non-significant predictors are plotted). For Experiments 3, 4, and 6, I report and visualise also the non-significant effect of group, because of the focus of these experiments on the comparison between the performances of different populations of participants.

2.10 Participants' recruitment and ethics statement

All participants recruited across the experiments of the current thesis were naive to the purpose of the experiment in which they took part, unfamiliar with the stimulus material, and none of them participated in more than one experiment. The experiments were approved by the Psychology Research Ethics Committee at the School of Philosophy, Psychology and Language Sciences at the University of Edinburgh (Ref: 12-1617) prior to starting the data collection, and written consent was collected from all participants at the beginning of each experimental session.

3 Semantic guidance of overt attention of younger and older adults during search

3.1 Introduction

Eye-tracking studies using arrays of objects have demonstrated that, during a search task, young adults preferentially look at regions of the array which contain objects sharing semantic features with the target, i.e., semantic relatedness effects (Belke et al., 2008; de Groot et al., 2016; Moores et al., 2003; Nuthmann et al., 2019). Although these studies agree that semantic information can guide eye movements during search, there are some controversies about the temporal dynamics of the semantic influence on overt attention. Moores et al. (2003) and Belke et al. (2008) reported semantic relatedness effects on the very first saccadic eye movement after the onset of the object array. Instead, de Groot et al. (2016) found that early visual attention was primarily driven by the visual similarity between the objects, whilst semantic information would mainly influence later eye movements. More recently, Nuthmann et al. (2019) re-analysed the data from de Groot et al. (2016) and, although they found a stronger influence of visual information than semantic information on attentional orienting, they also found evidence of semantic relatedness effects on initial eye movements. This would indicate that the semantic features of objects can be processed early in extra-foveal vision to a degree sufficient to guide overt attention from the very first fixation after the onset of a visual context.

Whether and to what extent object semantics can be processed outside the fovea to guide the allocation of overt attention has been investigated also in older adults, with contrasting results. Boucart et al. (2014) showed that the semantic guidance of attention in naturalistic scenes is impaired in older adults, presumably because of an age-related dysfunction of the magnocellular pathway, which would hinder their ability to extra-foveal semantic processing (Lenoble et al., 2013). Critically, since Boucart et al. (2014) presented the scenes only for 1 second and examined only the accuracy of the first saccade (which occurred on average 250 ms after scene onset), age-related differences in the semantic capture of attention might have also resulted from a generalized slowing of cognitive processes associated to ageing (Salthouse, 1996, 2012). That is, age-related differences in semantic guidance might have been less evident if older adults had had more time to explore the scenes, process semantic features and, then, select relevant objects to fixate. This interpretation is supported by the findings of a recent visual search study by Borges et al. (2020). Their analysis on the latency to first fixation (z-scored to control for general slowing effects) showed that target objects inconsistent with the scene were fixated earlier than consistent ones, in both younger and older adults, with no difference among groups. This would indicate that older adults can access object semantic information in extra-foveal vision as efficiently as younger adults to guide eye movements.

In this Chapter, I employed a new experimental paradigm (see Figure 5 in Chapter 1) to examine the influence of object semantics on eye-movement guidance in younger and older adults. In my task, participants searched for a target in object arrays comprising a critical object and distractors. At the beginning of the trial, they were presented with the name of the target to search which cued attention to the critical object as the search target (target-present trials), or as target semantically related competitor (target-absent trials). I manipulated the semantic relatedness of the critical objects and the distractors so that either the critical object and the distractors belonged to the same semantic category (related), or the distractors were of the same semantic category but the critical object of a different one (unrelated). Previous research demonstrated that, in visual search, overt attention is guided by the analysis of the semantic features that are shared (or not) between the search target and the distractor objects (Belke et al., 2008; de Groot et al., 2016; Moores et al., 2003; Nuthmann et al., 2019). Also, when distractors differ homogenously from the target on a target-defining feature (e.g., the colour), the guidance of such feature on directing overt attention is stronger compared to when the distractors are more heterogeneous (Duncan & Humphreys, 1989). In line with this research, I expected the critical object to capture overt attention earlier when semantically unrelated than related to the distractors. When the critical object (e.g., a car) was semantically related to the distractors (e.g., all vehicles), all objects equally competed for visual attention. When the critical object was instead semantically unrelated to the semantically homogeneous distractors (e.g., all kitchen items), it would be the only object sharing semantic features with the target and would thus capture overt attention. Such finding would demonstrate that the semantic features of objects are processed in extra-foveal vision and used to guide the allocation of visual attention.

I also manipulated the visual saliency of the critical object so that it was either among the most or the least salient objects in the array. This manipulation allowed me to examine the role played by low-level visual information in overt attention during a cued search task.

Three experiments were conducted: in Experiments 1 and 2, young adults were presented with arrays of different sizes (3, 5, 7) and asked to search for a target object in target-absent (Experiment 1) and target-present (Experiment 2) object arrays. In Experiment 3, younger and healthy older adults performed the same visual search task, on target-absent and target-present five-object arrays.

3.2 Experiment 1

Experiment 1 aimed to provide fresh evidence that object semantic information can be processed early in extra-foveal vision and used to guide initial eye movements during search on target-absent object arrays (e.g., Nuthmann et al., 2019). In this experiment, the cue word for the search target always referred to an object that did not appear in the array, and it was semantically related to the critical object (e.g., the cue word was airplane and the critical object was instead a car; See Figure 5 in Chapter 1).

I expected the critical object to capture overt attention earlier when semantically unrelated than related to the distractors. More specifically, if object semantics can be processed early in extra-foveal vision and guide overt attention promptly, I expected to observe semantic relatedness effects on the probability of the very first fixation after the onset of the array, and be corroborated by the measure of search latency, i.e., the time it takes for the critical object to be looked at for the first time.

Also, if the semantics of all objects in the array are computed in parallel, then a critical object that is semantically unrelated to the other distractors should display the same advantage to be prioritized over a semantically related critical object even when increasing the number of the distractors (i.e., a semantic “pop-out” effect).

The above predictions are all about the time-course of target identification, but important differences may also manifest in the processing time, such as in the duration of the first fixation to the critical object. For example, in a visual memory task, Henderson, Pollatsek, and Rayner (1987) found shorter first-fixation durations on a critical object when it was presented together with semantically related than unrelated distractors. They explained this result in terms of positive priming arising from having previously fixated semantically related objects. In line with this result, I expected to extend this finding to a visual search task, and hence find shorter first-gaze durations to the critical object when semantically related as opposed to unrelated to the distractors.

Finally, I predicted visual saliency to not play any role in search guidance, as previously shown by Chen and Zelinsky (2006).

3.2.1 Methods

3.2.1.1 Participants

A total of 72 participants (53 women), students at the University of Edinburgh and aged between 18 and 30 years (M = 19.49, SD = 2.30), participated in the experiment for either course credits or a £3.50 honorarium. All participants were native English speakers and had a normal or corrected-to-normal vision.

3.2.1.2 Design

A 2x2x3 mixed factorial design was used with two within-participants variables, Semantic Relatedness (unrelated, related) and Visual Saliency (non-salient, salient) and a between-participants variable, Set Size (3, 5, 7), with participants equally divided among the different set sizes (i.e., 24 participants each).

3.2.1.3 Stimuli

The object arrays were presented at a resolution of 1024 x 768 pixels, at a viewing distance of 82 cm (28.07° and 21.40° of visual angle on the horizontal and on the vertical axis, respectively). Object pictures had a size of 150 x 150 pixels (4.18° x 4.23° of visual angle) and were arranged on an imaginary circle such that the midpoint of each object was equidistant from the centre of the array (corresponding to the starting fixation point) and from the two adjacent objects' midpoints. The circle had a fixed radius of 344 pixels (9.62°) while the distance between objects changed depending on the number of objects in the array: 595.83 (16.67°), 404.40 (11.31°), and 298.51 (8.35°) pixels for set sizes 3, 5 and 7, respectively.

A total of 224 object pictures were used to create the experimental arrays. Of these, I selected 32 objects to be used as critical objects. A total of 384 unique experimental arrays were constructed by crossing the visual saliency (non-salient, salient) and the semantic relatedness (unrelated, related) of the 32 critical objects (128 items, i.e., 32 * 4), independently for three set sizes (384 items, i.e., 128 * 3).

For each set size, I also constructed 32 filler arrays (96 items in total, i.e., 32 * 3) using object pictures from the BOSS database (Brodeur et al., 2010, 2014) that did not appear in the experimental arrays. Each participant saw the same 32 fillers and 32 unique experimental arrays, which were counterbalanced across the conditions of visual saliency and semantic relatedness using a Latin square rotation, in one specific set size (i.e., either 3, 5, or 7). In both experimental and filler trials, a cue word of the search target, i.e., the target name, was presented at the centre of the screen prior to the onset of the search array. The cue word did not refer to any object in the experimental arrays (i.e., target-absent trials), and it was either semantically related to the critical object in the display but unrelated to all other semantically homogenous distractor objects (i.e., LSA scores, $M = .02$, $SD = .11$), or semantically related to all objects ($M = .31$, $SD = .22$), $t(95) = 11.18$, $p < .001$, $r = .75$; See Supplemental Materials C for the list of target-absent experimental trials. The filler arrays, instead, always had an object depicted in it that the cue word referred to (i.e., target-present trials). The filler arrays were used to guarantee a balanced distribution of yes/no response, as the target of search was visually present on 50% of the total 64 trials performed, and to keep participants actively engaged in the task.

3.2.1.4 Procedure

At the beginning of each experimental session, a 9-point calibration and validation procedure were run to set up the eye-tracking accuracy. Each trial began with a drift correction after which a cue word of the search target, i.e., the target name, was prompted at the centre of the screen for 800 milliseconds (ms). I preferred to use words rather than pictures as cues to avoid participants using knowledge of the specific visual features of the target to search for it within the object arrays. The presentation of the target name was followed by a central fixation cross and then the object array. The size of the fixation cross was 42 x 42 pixels (1.20° x 1.21° of visual angle) and it was surrounded by an invisible bounding box of 70 x 70 pixels (1.96° x 1.96° of visual angle) that had to be looked at for 100 ms to trigger the presentation of the object array, i.e., the beginning of the trial.

Participants received written instruction and were asked to indicate, as quickly and accurately as possible, whether the target was present or absent in the object array by pressing the left or the right arrow key on a computer keyboard (search response), respectively. If participants pressed the left arrow key (i.e., the target was present), the object array was replaced by a number array. Participants were then asked to type in the number matching the target location using the numeric keypad (number response). This provided me with additional verification of the search accuracy: I regarded as accurately responding to a target-present trial when both the search response and the number response were accurate. If participants pressed the right arrow key (i.e., the target was absent), they moved directly to the next trial. They were given 5000 ms to complete the search, otherwise, a null response was logged (see Figure 10 for an example of a trial run). Each participant completed 4 practice trials and 64 randomized trials of which 32 were experimental and 32 filler trials. The experimental session lasted approximately 20 minutes.

3.2.2 Analyses

The dependent variables measured were response accuracy, response time (natural log-scale), the probability of immediate fixation, search latency, and first-gaze duration on the critical object (See Chapter 2 for a detailed description of the dependent variables). I analysed the data from the 2,304 experimental trials only (i.e., 32 trials x 72 participants). Of these trials, 112 trials were discarded because of machine error (no eye movement was recorded). On the remaining trials (2,192), I analysed the response accuracy. The response time was computed on accurate trials only (2,143), whereas the eye-movement measures were computed only on accurate trials in which the critical object was fixated at least once (1,917).

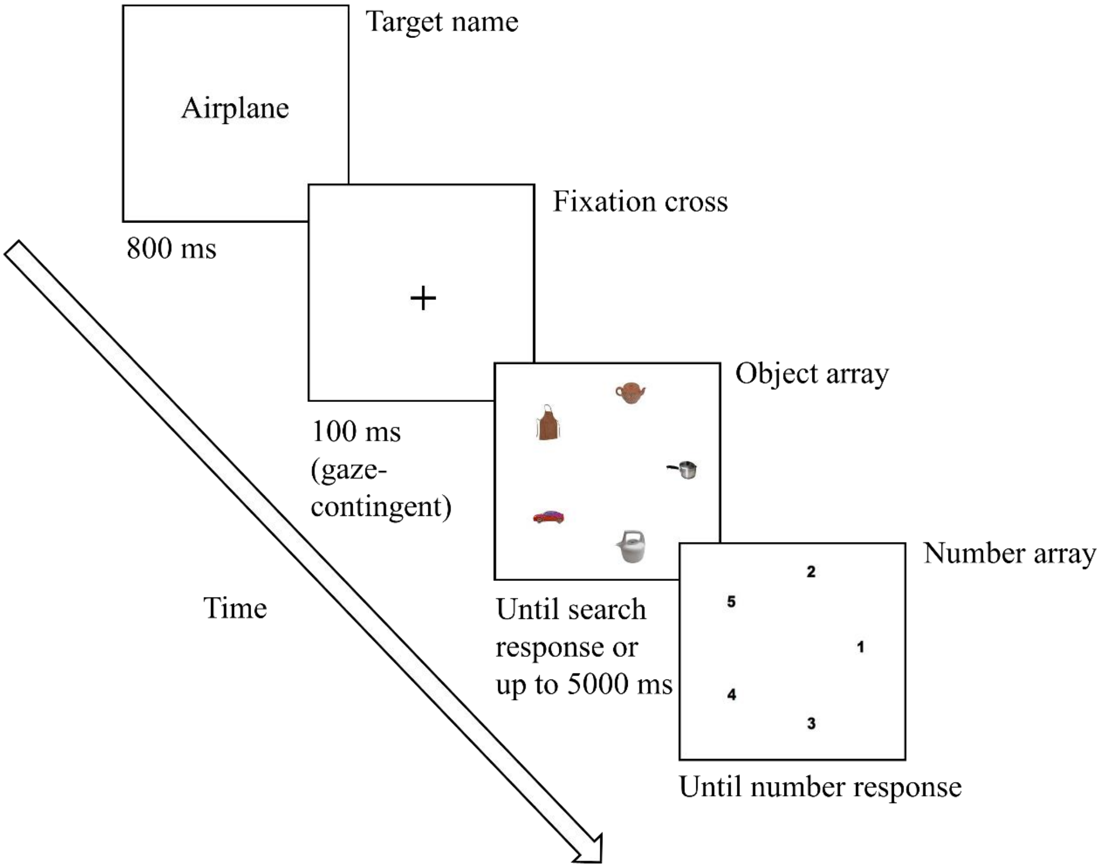


Figure 10. Example of a trial run. The target name was cued at the beginning of the trial. Then, a fixation cross appeared which needed to be fixated for 100 ms to trigger the presentation of the object array. When the participant responded that a target was found, the object array was replaced with a number array. The participant had to indicate then the remembered location of the object in the number array. When the participant responded that the target was not found, the object array was immediately followed by the next trial.

Data were analysed by using used linear and generalized linear mixed-effects models (G/LMM). In particular, the fixed effects considered, and centred to reduce co-linearity, were: Semantic Relatedness (unrelated = -.5, related = .5), Visual Saliency (non-salient = -.5, salient = .5), Set Size (3, 5, 7), where I used the set size of 3 as the reference level (3 vs. 5: 3 = -.5, 5 = .5; and 3 vs. 7: 3 = -.5, 7 = .5), and Visual Similarity, (dissimilar = -.5, similar = .5). The random variables included in the models, both as intercepts and slopes, were Participant (72) and Item (384).

3.2.3 Results

Before presenting the results of the analyses, it is worth highlighting that visual saliency was never included, as a significant main effect, in any best-fitting model on any of the measures analysed in this experiment.

3.2.3.1 Accuracy and response time

On response accuracy, there was a significant main effect of semantic relatedness, whereby accuracy was higher when the critical object was semantically unrelated (M = .99, SD = .10) than related to the distractors (M = .97, SD = .18); β = - 7.94, SE = 2.07, z = - 3.84, p< .001.

On response times (Figure 11), I found significant main effects of set size and semantic relatedness. Search responses were faster for set size 3 as compared to 5 and 7, and when the critical object and distractors were semantically unrelated than related. I also found significant two-way interactions between semantic relatedness and set size, whereby response times were faster when the critical object was semantically unrelated to the distractors, especially for set sizes 5 and 7; and between visual similarity and set size, whereby response times were faster when the critical object and distractors were visually dissimilar, especially for set sizes 5 and 7. There was also a significant three-way interaction between semantic relatedness, visual similarity and set size, with faster response times when the critical object was semantically unrelated and visually dissimilar to the distractors, especially for set size 7 (See Table 3 for the model output).

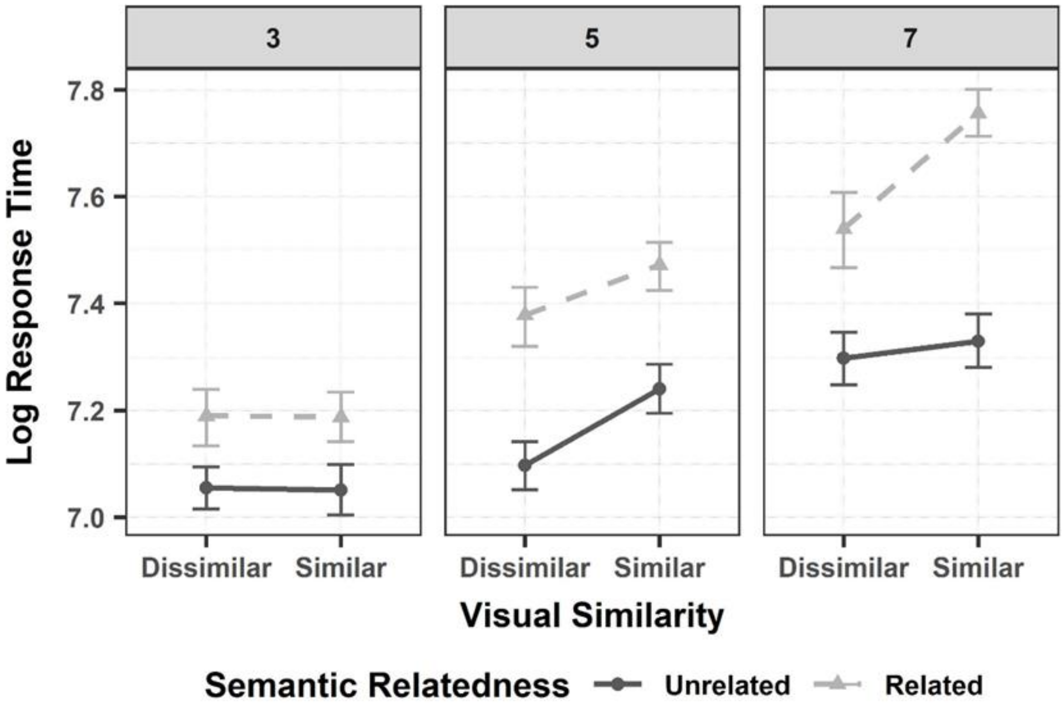


Figure 11. Mean response time (natural-log scale) for set sizes 3 (left panel), 5 (central panel) and 7 (right panel), with the two levels of visual similarity (dissimilar, similar) on the x-axis. The semantic relatedness of the critical object is marked using line types and colour (unrelated: dark grey, solid line; related: light grey, dashed line). Error bars represent 95% confidence intervals around the mean.

Table 3

Linear Mixed-effects Model Output for Log Response Time

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
	Intercept	7.12	0.04	169.60	**< 0.001**
	Semantic Relatedness	0.14	0.04	3.95	**< 0.001**
	Set size (3 vs. 5)	0.18	0.06	3.06	**0.003**
	Set size (3 vs. 7)	0.37	0.06	6.18	**< 0.001**
Log Response Time	Visual Similarity	- 0.00	0.03	- 0.05	0.96
	Semantic Relatedness:Set size (3 vs. 5)	0.13	0.05	2.61	**0.01**
	Semantic Relatedness:Set size (3 vs. 7)	0.20	0.05	3.97	**< 0.001**
	Semantic Relatedness:Visual Similarity	0.05	0.07	0.75	0.46
	Visual Similarity:Set size (3 vs. 5)	0.10	0.05	2.13	**0.03**
	Visual Similarity:Set size (3 vs. 7)	0.10	0.05	2.16	**0.03**
	Semantic Relatedness:Visual Similarity:Set size (3 vs. 5)	- 0.06	0.10	- 0.58	0.56
	Semantic Relatedness:Visual Similarity:Set size (3 vs. 7)	0.23	0.10	2.32	**0.02**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Semantic Relatedness (unrelated = -.5, related = .5), Set Size (3, 5, 7), and Visual Similarity (dissimilar = -.5, similar = .5). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

3.2.3.2 Probability of immediate fixation, search latency, and first-gaze duration

On the probability of immediate fixation (Figure 12), I found significant main effects of set size and semantic relatedness. The probability of looking at the critical object on the first fixation after array onset was higher for set size 3 than 5 and 7, and when it was semantically unrelated than related to the distractors (Refer to Table 4 for the model output).

When looking at the search latency (Figure 13), I found a significant main effect of set size, with the critical object looked at earlier in set size 3 than 5 and 7. Moreover, there was a significant main effect of semantic relatedness, whereby participants looked at the critical object earlier when it was semantically unrelated than related to the distractors. This was especially the case for set sizes 5 and 7 (for the two-way significant interaction of semantic relatedness and set size) (See Table 5 for the model output).

On the first-gaze duration (Figure 14), there was a significant main effect of set size, with the critical object fixated for longer on set size 3 than 5 and 7. There was also a significant main effect of semantic relatedness: the critical object was fixated for less time when semantically related than unrelated to the distractors (See Table 6 for the model output).

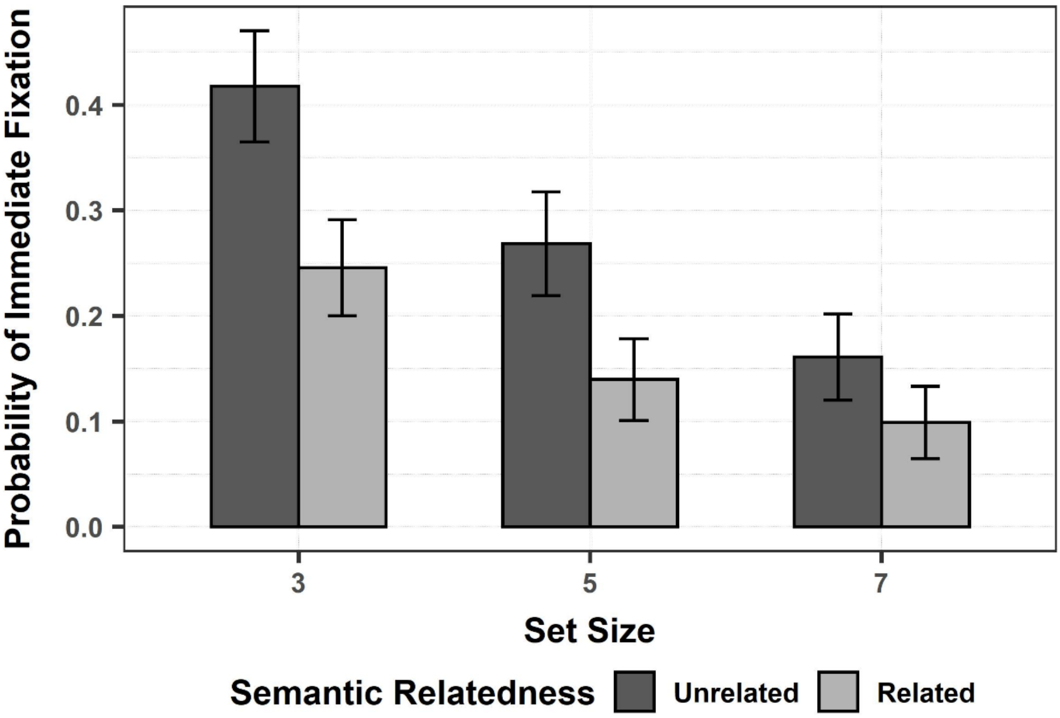


Figure 12. Mean probability of immediate fixation to the critical object (proportions) for set sizes 3, 5, and 7 (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 4

Generalized Linear Mixed-effects Model Output for the Probability of Immediate Fixation to the Critical Object

Dependent Variable	Predictor	β	SE	z-value	Pr (> | z |)
Probability of Immediate Fixation	Intercept	- 0.84	0.12	- 7.13	**< 0.001**
	Set size (3 vs. 5)	- 0.76	0.18	- 4.30	**< 0.001**
	Set size (3 vs. 7)	- 1.37	0.19	- 7.10	**< 0.001**
	Semantic Relatedness	- 0.83	0.15	- 5.42	**< 0.001**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Set Size (3, 5, 7) and Semantic Relatedness (unrelated = -.5, related = .5). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

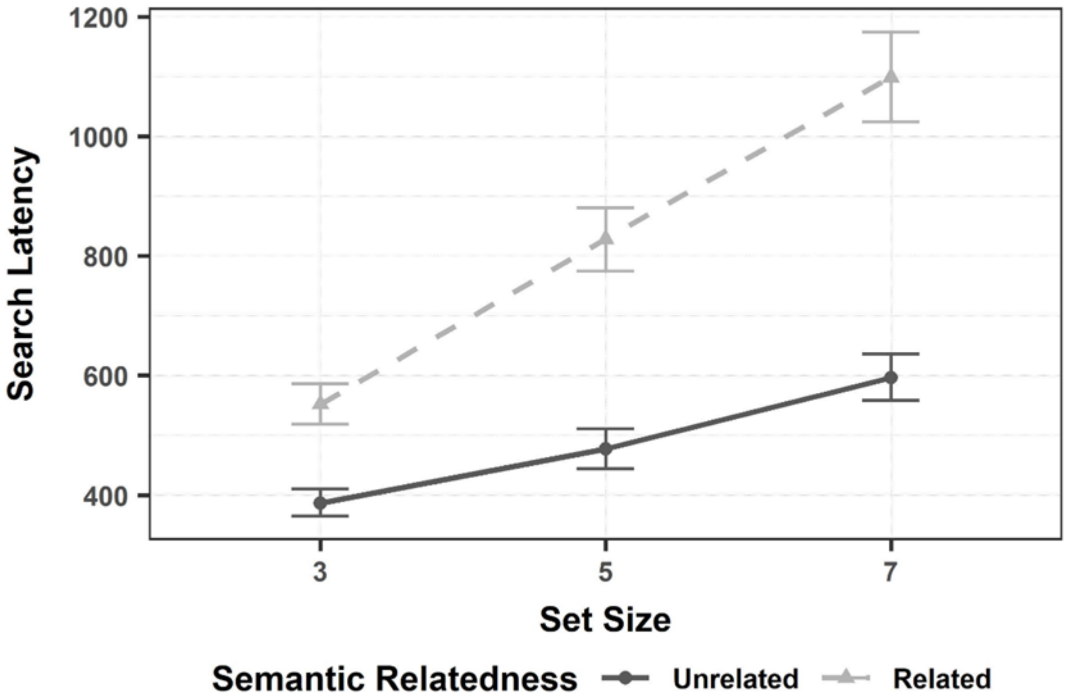


Figure 13. Mean search latency (ms) on the critical object for set sizes 3, 5, and 7 (on the x-axis) with the semantic relatedness of the critical object marked using line types and colour (unrelated: dark grey, solid line; related: light grey, dashed line). Error bars represent 95% confidence intervals around the mean.

Table 5

Linear Mixed-effects Model Output for the Search Latency on the Critical Object

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
Search Latency	Intercept	472.99	24.99	18.93	**< 0.001**
	Semantic Relatedness	167.54	42.62	3.93	**< 0.001**
	Set size (3 vs. 5)	182.13	35.68	5.10	**< 0.001**
	Set size (3 vs. 7)	380.72	35.79	10.64	**< 0.001**
	Semantic Relatedness:Set size (3 vs. 5)	186.76	61.01	3.06	**0.002**
	Semantic Relatedness:Set size (3 vs. 7)	320.56	61.32	5.23	**< 0.001**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Semantic Relatedness (unrelated = -.5, related = .5) and Set Size (3, 5, 7). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

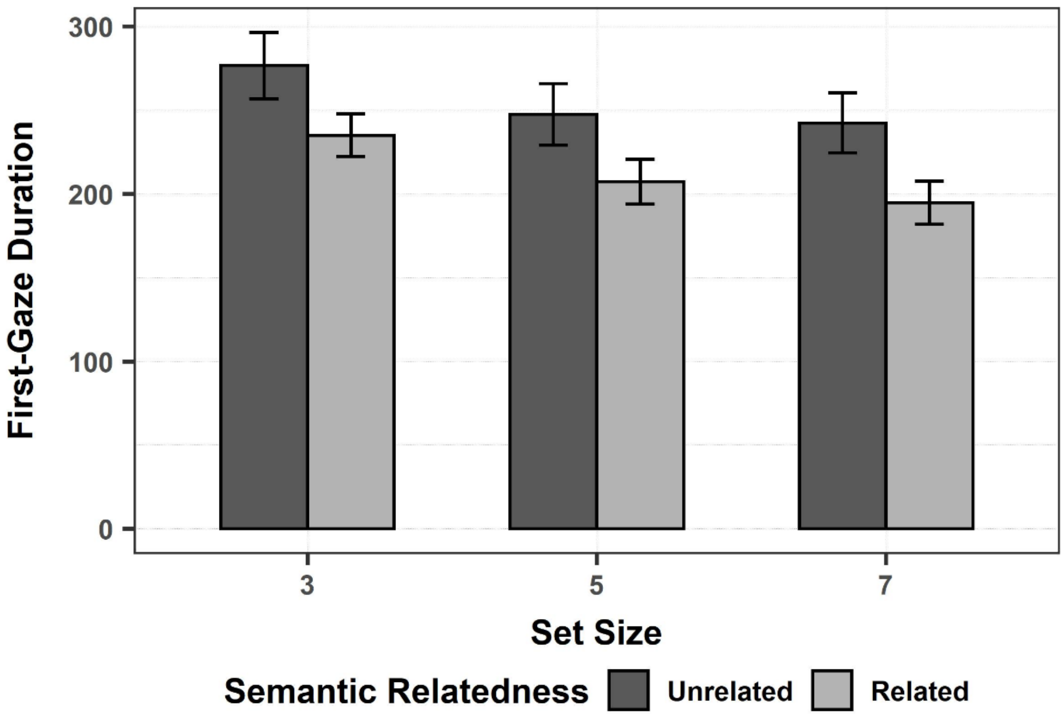


Figure 14. Mean first-gaze duration (ms) on the critical object for set sizes 3, 5, and 7 (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 6

Linear Mixed-effects Model Output for the First-gaze Duration on the Critical Object

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
First-gaze Duration	Intercept	255.00	10.32	24.71	**< 0.001**
	Semantic Relatedness	- 40.97	9.71	- 4.22	**< 0.001**
	Set size (3 vs. 5)	- 31.05	14.70	- 2.11	**0.04**
	Set size (3 vs. 7)	- 39.20	14.73	- 2.66	**0.01**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Semantic Relatedness (unrelated = -.5, related = .5) and Set Size (3, 5, 7). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

3.2.4 Discussion

Experiment 1 showed that a critical object was more likely to attract the very first fixation after the onset of an object array, and overall be inspected earlier and for longer, when it was semantically unrelated than related to the distractor objects. Semantic relatedness effects were consistently found for increasing set sizes and were independent of visual saliency, which did not play any role in guiding overt attention. These results suggest that object semantics can be extracted early in extra-foveal vision to capture overt attention from the very first fixation, consistently with previous findings of semantic relatedness effects on initial eye movements in target-absent object arrays (Belke et al., 2008; Moores et al., 2003; Nuthmann et al., 2019).

In Experiment 1, the critical object was a target semantically related competitor. This design was conceived to replicate the results by Nuthmann et al. (2019), who used target-absent experimental trials and target-present filler trials. Then, I decided to conduct Experiment 2 to examine the opposite scenario, i.e., target-present experimental trials and target-absent filler trials, in order to investigate whether the results would corroborate.

3.3 Experiment 2

The aim of Experiment 2 was to provide further evidence of semantic relatedness effects on initial eye movements during search on target-present object arrays (Belke et al., 2008; Moores et al., 2003).

Experiment 2 used the same methodology as Experiment 1 (i.e., design, stimuli, procedure), with the exception that the cue word presented at the beginning of trials always referred to the critical object, which was the target of search (target-present experimental trials), and it did not refer to any object in the filler arrays (i.e., target-absent filler trials); See Supplemental Materials C, for the list of target-present experimental trials. A total of 72 young adults (50 women), students at the University of Edinburgh and aged between 18 and 30 years ($M = 22.28$, $SD = 2.79$), participated in Experiment 2 for either course credits or a £3.50 honorarium. All participants were native English speakers and had a normal or corrected-to-normal vision. As in Experiment 1, participants were equally divided into three groups, i.e., 24 participants for each set size (3, 5, and 7). Each participant completed 64 trials, comprising 32 target-present experimental trials and 32 target-absent filler trials. The dependent variables measured, as well as the fixed and random effects included in the models, were the same as those presented in Experiment 1. The analysis considered the 2,304 experimental trials only (i.e., 32 trials x 72 participants). Of these trials, 83 trials were discarded because of machine error (no eye movement was recorded). On the remaining trials (2,221), I analysed the response accuracy. The response time was computed on accurate trials only (2,057), whereas eye-movement measures were computed only on accurate trials in which the critical object was fixated at least once (2,050). I also conducted a follow-up analysis where I compared the data of target-absent (Experiment 1) vs. target-present (Experiment 2) within the same model as a between-participants variable to increase the statistical sample and examine whether effects of semantic relatedness vary according to the presence of the target. I expected to replicate the findings of semantic relatedness effects on eye-movement behaviour of Experiment 1 and, in line with previous literature (Belke et al., 2008; Moores et al., 2003), I also expected the presence of the target in the array to reduce these effects because participants might rely more on visual information to facilitate search (Huettig & Altmann, 2005; Huettig & Mcqueen, 2007).

3.3.1 Results

As in Experiment 1, low-level visual saliency was never included, as a significant main effect, in any best-fitting model on any of the measures analysed in Experiment 2.

3.3.1.1 Accuracy and response time

No predictor had a significant effect on response accuracy, which was at ceiling, and hence no further discussed.

On response times (Figure 15), I found a significant main effect of set size, with faster response times in set size 3 than 7. Moreover, there was a significant main effect of visual similarity. Response times were faster when the critical object was visually dissimilar than similar to the distractors. There was also a significant main effect of semantic relatedness, whereby response times were faster when the critical object was semantically unrelated than related to the distractors. This was especially the case for set size 7 (for the

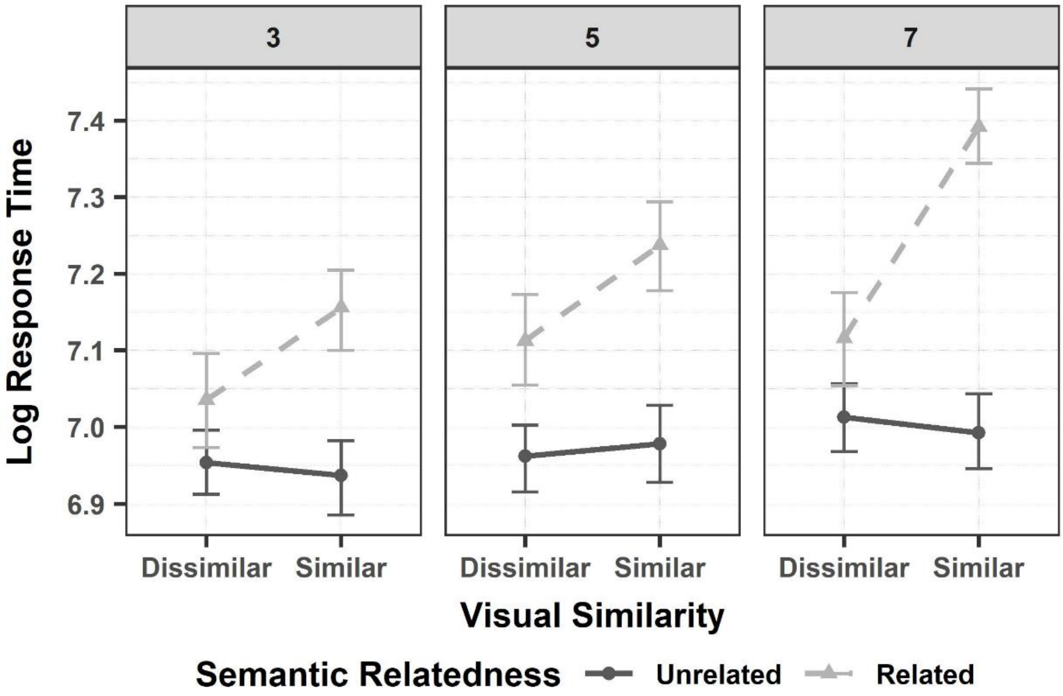


Figure 15. Mean response time (natural-log scale) for set sizes 3 (left panel), 5 (central panel) and 7 (right panel), with the two levels of visual similarity (dissimilar, similar) on the x-axis. The semantic relatedness of the critical object is marked using line types and colour (unrelated: dark grey, solid line; related: light grey, dashed line). Error bars represent 95% confidence intervals around the mean.

Table 7

Linear Mixed-effects Model Output for Log Response Time

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
Log Response Time	Intercept	7.02	0.03	201.23	**< 0.001**
	Semantic Relatedness	0.14	0.03	4.17	**< 0.001**
	Visual Similarity	0.08	0.02	4.21	**< 0.001**
	Set size (3 vs. 5)	0.06	0.05	1.17	0.24
	Set size (3 vs. 7)	0.11	0.05	2.31	**0.02**
	Semantic Relatedness:Visual Similarity	0.19	0.04	4.23	**< 0.001**
	Semantic Relatedness:Set size (3 vs. 5)	0.07	0.05	1.45	0.15
	Semantic Relatedness:Set size (3 vs. 7)	0.11	0.05	2.26	**0.02**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Semantic Relatedness (unrelated = -.5, related = .5), Visual Similarity (dissimilar = -.5, similar = .5), and Set Size (3, 5, 7). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

two-way significant interaction of semantic relatedness and set size) and when the critical object was visually dissimilar to the distractors (for the two-way interaction of semantic relatedness and visual similarity) (See Table 7 for the model output).

3.3.1.2 Probability of immediate fixation, search latency, and first-gaze duration

On the probability of immediate fixation (Figure 16), I found significant main effects of set size and semantic relatedness. The probability of looking at the critical object on the first fixation after array onset was higher for set size 3 than 5 and 7, and when it was semantically unrelated than related to the distractors (Refer to Table 8 for the model output).

On the search latency (Figure 17), I found a significant main effect of set size, with the critical object looked at earlier in set size 3 than 5 and 7. Moreover, there was a significant main effect of semantic relatedness, whereby participants looked at the critical object earlier when it was semantically unrelated than related to the distractors. This was especially the case for set size 7 (for the two-way significant interaction of semantic relatedness and set size) and when the critical object was visually dissimilar to the distractors (for the two-way interaction of semantic relatedness and visual similarity). I also found a significant two-way interaction between visual similarity and set size, with shorter search latencies when the critical object and distractors were visually dissimilar, especially on set size 7 (Refer to Table 9 for the model output).

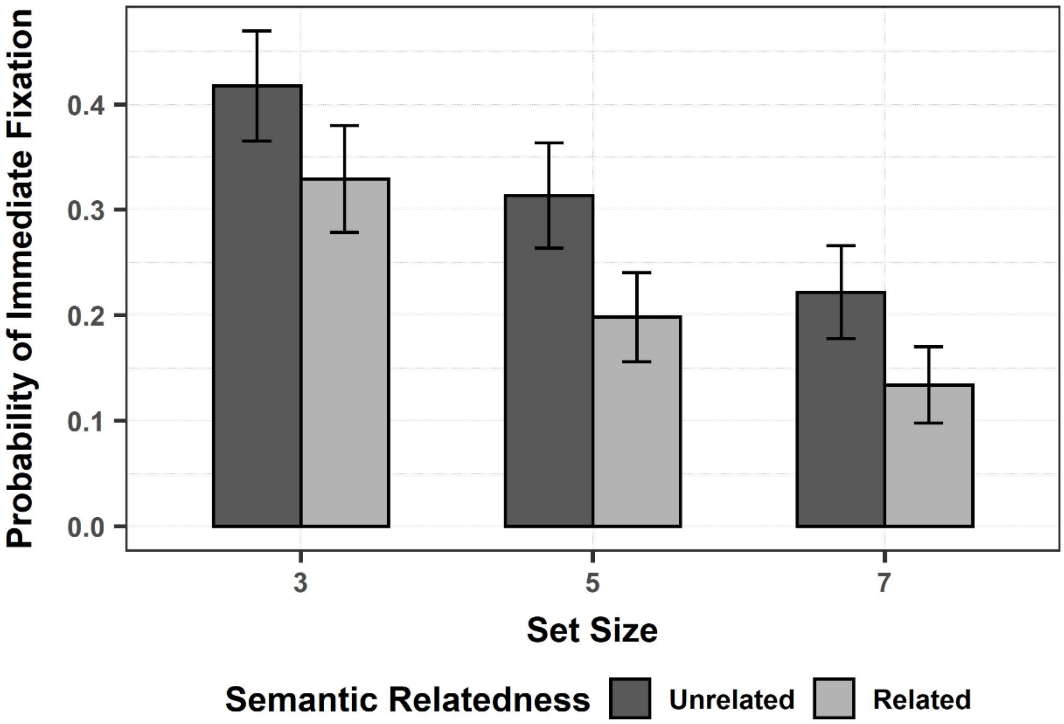


Figure 16. Mean probability of immediate fixation to the critical object (proportions) for set sizes 3, 5, and 7 (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 8

Generalized Linear Mixed-effects Model Output for the Probability of Immediate Fixation to the Critical Object

Dependent Variable	Predictor	β	SE	z-value	Pr (> | z |)
Probability of Immediate Fixation	Intercept	- 0.66	0.14	- 4.66	**< 0.001**
	Set size (3 vs. 5)	- 0.67	0.20	- 3.29	**0.001**
	Set size (3 vs. 7)	- 1.20	0.21	- 5.68	**< 0.001**
	Semantic Relatedness	- 0.62	0.15	- 4.10	**< 0.001**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Set Size (3, 5, 7) and Semantic Relatedness (unrelated = -.5, related = .5). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

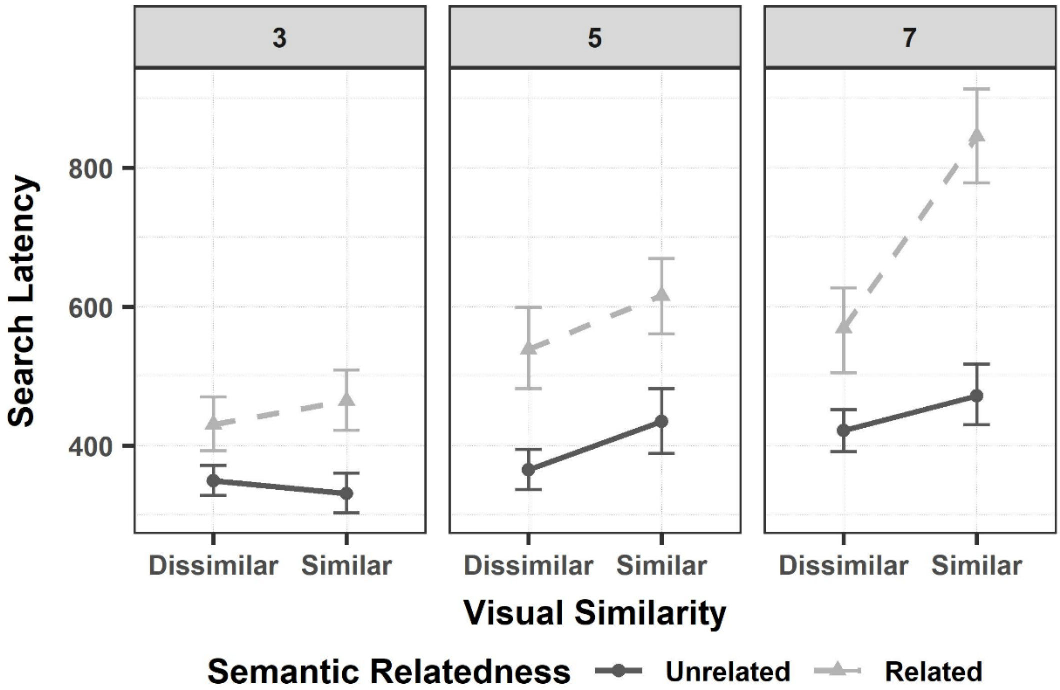


Figure 17. Mean search latency (ms) on the critical object for set sizes 3 (left panel), 5 (central panel) and 7 (right panel) with the two levels of visual similarity (dissimilar, similar) on the x-axis. The semantic relatedness of the critical object is marked using line types and colour (unrelated: dark grey, solid line; related: light grey, dashed line). Error bars represent 95% confidence intervals around the mean.

Table 9

Linear Mixed-effects Model Output for the Search Latency on the Critical Object

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
Search Latency	Intercept	394.12	21.55	18.29	**< 0.001**
	Semantic Relatedness	106.73	37.30	2.86	**0.005**
	Set size (3 vs. 5)	99.73	30.40	3.28	**0.001**
	Set size (3 vs. 7)	189.73	30.42	6.24	**< 0.001**
	Visual Similarity	7.04	35.02	0.20	0.84
	Visual Similarity:Set size (3 vs. 5)	78.76	49.16	1.60	0.11
	Visual Similarity:Set size (3 vs. 7)	157.73	49.42	3.19	**0.002**
	Semantic Relatedness:Visual Similarity	104.64	40.76	2.57	**0.01**
	Semantic Relatedness:Set size (3 vs. 5)	80.12	52.53	1.53	0.13
	Semantic Relatedness:Set size (3 vs. 7)	155.07	52.69	2.94	**0.004**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Semantic Relatedness (unrelated = -.5, related = .5), Set Size (3, 5, 7), and Visual Similarity (dissimilar = -.5, similar = .5). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

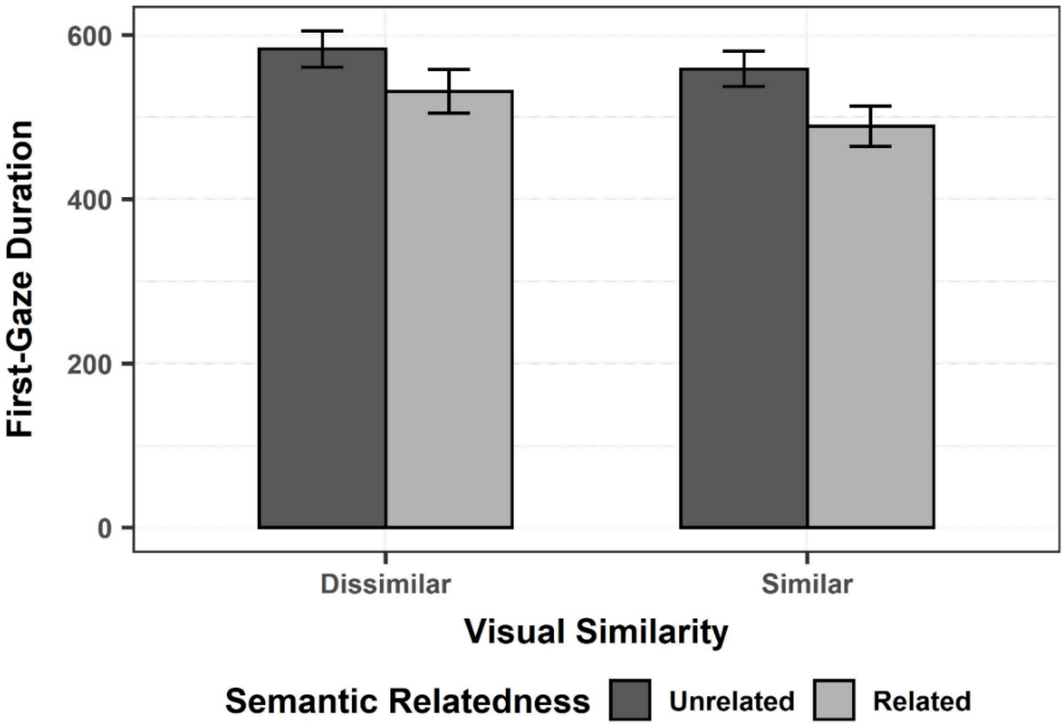


Figure 18. Mean first-gaze duration (ms) on the critical object with the two levels of visual similarity (dissimilar, similar) on the x-axis, in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 10

Linear Mixed-effects Model Output for the First-gaze Duration on the Critical Object

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
First-gaze Duration	Intercept	540.18	12.47	43.33	**< 0.001**
	Semantic Relatedness	- 67.01	12.23	- 5.48	**< 0.001**
	Visual Similarity	- 33.02	15.27	- 2.16	**0.03**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Semantic Relatedness (unrelated = -.5, related = .5) and Visual Similarity (dissimilar = -.5, similar = .5).

On the first-gaze duration (Figure 18), I found significant main effects of semantic relatedness and visual similarity, with the critical object fixated for less time when semantically related than unrelated, and visually similar than dissimilar to the distractors (See Table 10 for the model output).

3.3.2 Follow-up analyses

Experiment 2 reported evidence of semantic relatedness effects on measures of attentional capture, as well as of fixation processing, during search on target-present trials. Then, to examine whether the effects of semantic relatedness varied according to the presence of the target, I gathered the data from Experiments 1 and 2 and analysed performance and eye-movement measures within statistical models including the same predictors as those used in the previous experiments, plus a further between-participants predictor, Target (Absent = -.5, Present = .5).

3.3.2.1 Accuracy and response time

Response accuracy was at ceiling (target-present: M = .93, SD = .26; target-absent: M = .98, SD = .15; β = - 4.96, SE = .81, z = - 6.14, p< .001), and hence not further discussed.

On response times (Figure 19), I found significant main effects of set size and semantic relatedness. Search responses were faster for set size 3 as compared to 5 and 7, and when the critical object and distractors were semantically unrelated than related. I also observed significant two-way interactions between target and set size, with faster response times on

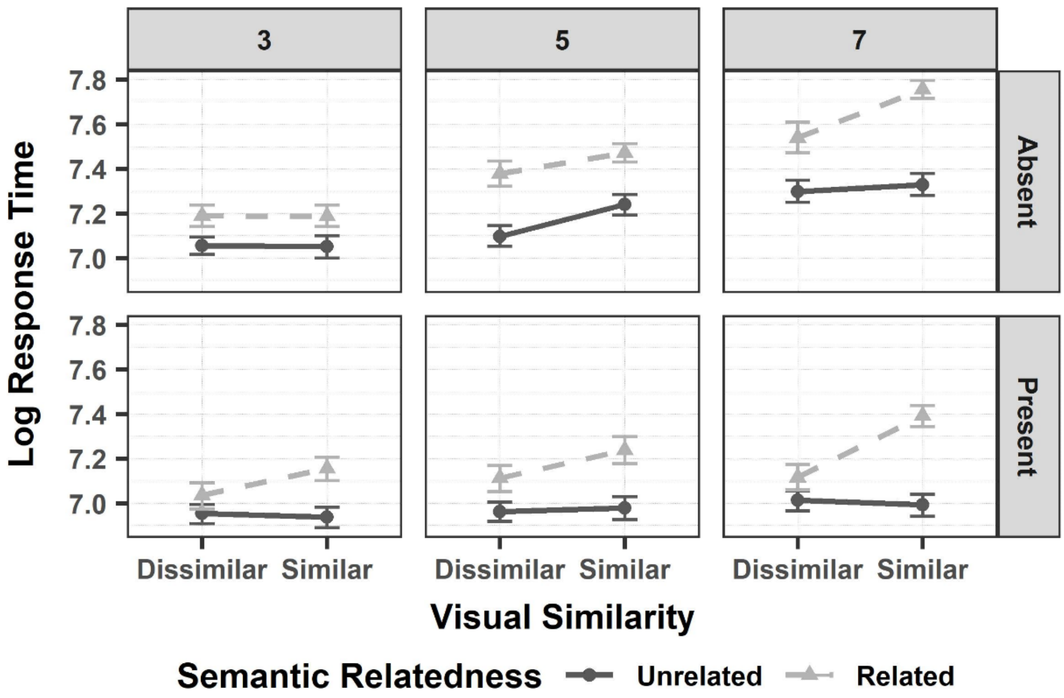


Figure 19. Mean response time (natural-log scale) for set sizes 3 (left panel), 5 (central panel) and 7 (right panel) on target-present and -absent trials, arranged over the rows of the panels, with the two levels of visual similarity (dissimilar, similar) on the x-axis. The semantic relatedness of the critical object is marked using line types and colour (unrelated: dark grey, solid line; related: light grey, dashed line). Error bars represent 95% confidence intervals around the mean.

target-present than -absent trials, especially for set size 7; between semantic relatedness and set size, whereby response times were faster when the critical object was semantically unrelated to the distractors, especially for set sizes 5 and 7; and between visual similarity and set size, whereby response times were faster when the critical object and distractors were visually dissimilar, especially for set size 7. There was also a significant three-way interaction between semantic relatedness, visual similarity and set size, with faster response times when the critical object was semantically unrelated and visually dissimilar to the distractors, especially for set size 7 (See Table 11 for the model output).

Table 11

Linear Mixed-effects Model Output for Log Response Time

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
Log Response Time	Intercept	7.07	0.03	252.93	**< 0.001**
	Semantic Relatedness	0.14	0.03	5.21	**< 0.001**
	Target	- 0.09	0.05	- 1.85	0.07
	Visual Similarity	0.02	0.03	0.77	0.44
	Set size (3 vs. 5)	0.12	0.04	2.98	**0.003**
	Set size (3 vs. 7)	0.24	0.04	6.01	**< 0.001**
	Semantic Relatedness:Visual Similarity	0.08	0.06	1.43	0.15
	Visual Similarity:Set size (3 vs. 5)	0.07	0.04	1.77	0.08
	Visual Similarity:Set size (3 vs. 7)	0.10	0.04	2.42	**0.02**
	Semantic Relatedness:Set size (3 vs. 5)	0.10	0.04	2.44	**0.02**
	Semantic Relatedness:Set size (3 vs. 7)	0.15	0.04	3.80	**< 0.001**
	Target:Set size (3 vs. 5)	- 0.12	0.07	- 1.65	0.10
	Target:Set size (3 vs. 7)	- 0.25	0.07	- 3.49	**< 0.001**
	Semantic Relatedness:Visual Similarity:Set size (3 vs. 5)	- 0.01	0.08	- 0.16	0.88
	Semantic Relatedness:Visual Similarity:Set size (3 vs. 7)	0.20	0.08	2.54	**0.01**
	Semantic Relatedness:Target:Set size (3 vs. 5)	- 0.07	0.05	- 1.50	0.14
	Semantic Relatedness:Target:Set size (3 vs. 7)	- 0.09	0.05	- 1.94	0.05

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Semantic Relatedness (unrelated = -.5, related = .5), Target (absent = -.5, present = .5), Visual Similarity (dissimilar = -.5, similar = .5), and Set Size (3, 5, 7). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

3.3.2.2 Probability of immediate fixation, search latency, and first-gaze duration

On the probability of immediate fixation (Figure 20), I found significant main effects of set size, target, and semantic relatedness. The probability of looking at the critical object on the first fixation after array onset was higher for set size 3 than 5 and 7, on target-present than target-absent trials, and when it was semantically unrelated than related to the distractors (Refer to Table 12 for the model output).

I also compared the probability of immediate fixation to the critical object, which I call observed probability (OP), for both the semantically

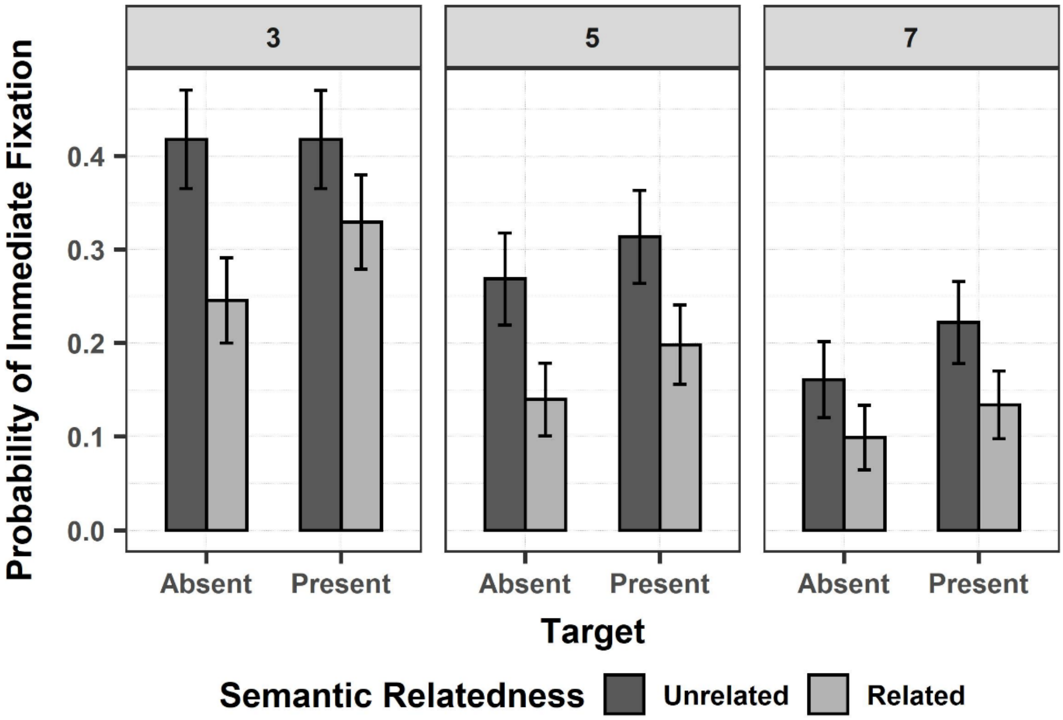


Figure 20. Mean probability of immediate fixation to the critical object (proportions) for set sizes 3 (left panel), 5 (central panel), and 7 (right panel) on target-present and -absent trials (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 12

Generalized Linear Mixed-effects Model Output for the Probability of Immediate Fixation to the Critical Object

Dependent Variable	Predictor	β	SE	z-value	Pr (> | z |)
Probability of Immediate Fixation	Intercept	- 0.73	0.10	- 7.18	**< 0.001**
	Set size (3 vs. 5)	- 0.71	0.15	- 4.77	**< 0.001**
	Set size (3 vs. 7)	- 1.24	0.15	- 8.02	**< 0.001**
	Semantic Relatedness	- 0.70	0.12	- 6.01	**< 0.001**
	Target	0.30	0.09	3.22	**0.001**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Set Size (3, 5, 7), Semantic Relatedness (unrelated = -.5, related = .5), and Target (absent = -.5, present = .5). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

related (OP*r*) and unrelated condition (OP*u*) of each set size, with the chance probability (CP) of looking at any object in the array calculated as *1/(N+1)*, where *N+1* is the total number of objects in the array, *N*, plus the blank section of the display (as fixations may also fall outside of the objects). This means that the CP equalled .25, .17, and .13 for set sizes 3, 5, and 7, respectively. Under binomial testing, I saw that the OP*u* was significantly higher than CP for set size 3 (M = .42, SD = .49), 5 (M = .29, SD = .45), and 7 (M = .19, SD = .39)(all ps<.001), whereas OP*r* did not differ significantly from CP, across all set sizes (3: M = .28, SD = .45; 5: M = .17, SD = .38; 7: M = .12, SD = .32; all ps>.05). I obtained identical results for the subset of trials where the very first fixation landed on an object (i.e., 2872 trials), and the CP was equal to *1/N*, which is .33, .20, and .14 for set sizes 3, 5, and 7, respectively. This analysis replicated the significant main effects of set size, target, and semantic relatedness: Set size 3 vs. 5 (3: M = .43, SD = .50 ; 5: M = .32, SD = .47; β = - .56, SE = .16, z = - 3.49, p< .001); Set size 3 vs.7 (7: M = .25, SD = .43; β = - .99, SE = .17, z = - 6.01, p< .001); Target (absent: M = .31, SD = .46; present: M = .38, SD = .49; β = .43, SE = .10, z = 4.33, p< .001); Semantic relatedness (unrelated: M = .41, SD = .49; related: M = .27, SD = .45; β = - .76, SE = .13, z = - 5.93, p< .001). Also, the OP*u* for each set size (3: M = .50, SD = .50; 5: M = .41, SD = .49; 7: M = .30, SD = .46) was significantly higher than CP (all ps<.001), whereas OP*r* did not differ significantly from CP, across all set sizes (3: M = .36, SD = .48; 5: M = .24, SD = .42; 7: M = .19, SD = .40)(all ps>.05).

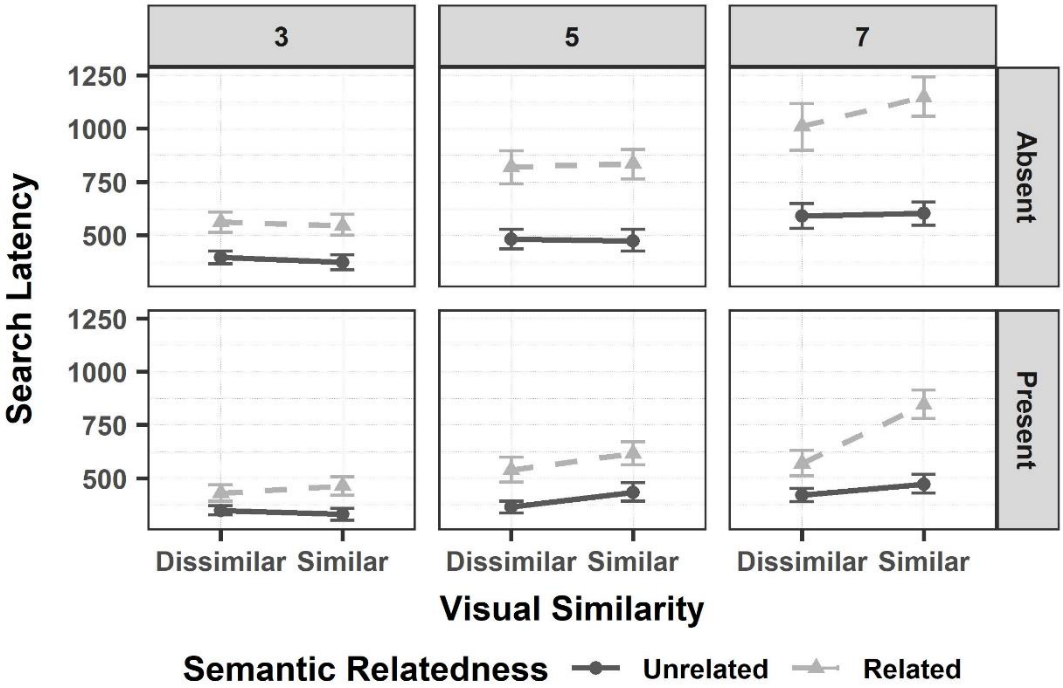


Figure 21. Mean search latency (ms) on the critical object for set sizes 3 (left panel), 5 (central panel) and 7 (right panel) on target-present and -absent trials, arranged over the rows of the panels, with the two levels of visual similarity (dissimilar, similar) on the x-axis. The semantic relatedness of the critical object is marked using line types and colour (unrelated: dark grey, solid line; related: light grey, dashed line). Error bars represent 95% confidence intervals around the mean.

When looking at the search latency (Figure 21), I found a significant main effect of set size, with the critical object looked at earlier in set size 3 than 5 and 7. Moreover, there was a significant main effect of target. The critical object was fixated earlier on target-present than target-absent trials. There was also a significant main effect of semantic relatedness, whereby participants looked at the critical object earlier when it was semantically unrelated than related to the distractors. This was especially the case for set sizes 5 and 7 (for the two-way significant interaction of semantic relatedness and set size) and when the critical object was visually dissimilar to the distractors (for the two-way interaction of semantic relatedness and visual

Table 13

Linear Mixed-effects Model Output for the Search Latency on the Critical Object

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
Search Latency	Intercept	430.88	17.83	24.17	**< 0.001**
	Semantic Relatedness	138.78	31.01	4.48	**< 0.001**
	Set size (3 vs. 5)	138.80	25.24	5.50	**< 0.001**
	Set size (3 vs. 7)	281.90	25.29	11.15	**< 0.001**
	Target	- 73.68	25.11	- 2.93	**0.004**
	Visual Similarity	- 9.05	31.93	- 0.28	0.78
	Semantic Relatedness:Target	- 64.33	35.48	- 1.81	0.07
	Semantic Relatedness:Set size (3 vs. 5)	128.63	43.87	2.93	**0.004**
	Semantic Relatedness:Set size (3 vs. 7)	229.37	44.13	5.20	**< 0.001**
	Target:Set size (3 vs. 5)	- 85.19	35.78	- 2.38	**0.02**
	Target:Set size (3 vs. 7)	- 181.27	35.81	- 5.06	**< 0.001**
	Target:Visual Similarity	68.99	22.76	3.03	**0.003**
	Visual Similarity:Set size (3 vs. 5)	53.37	45.21	1.18	0.24
	Visual Similarity:Set size (3 vs. 7)	130.56	45.43	2.87	**0.004**
	Semantic Relatedness:Visual Similarity	83.23	36.43	2.29	**0.02**
	Semantic Relatedness:Target:Set size (3 vs. 5)	- 94.05	50.72	- 1.85	0.06
	Semantic Relatedness:Target:Set size (3 vs. 7)	- 123.91	51.03	- 2.43	**0.01**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Semantic Relatedness (unrelated = -.5, related = .5), Set Size (3, 5, 7), Target (absent = -.5, present = .5), and Visual Similarity (dissimilar = -.5, similar = .5). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

similarity). I also found significant two-way interactions between target and set size, with the critical object fixated earlier on target-present than -absent trials, especially on set sizes 5 and 7; between visual similarity and target, whereby the critical was looked at earlier when it was visually dissimilar from the distractors, especially on target-present trials; and between visual similarity and set size, with shorter search latencies when the critical object and distractors were visually dissimilar, especially on set size 7. Finally, there was a significant three-way interaction between semantic relatedness, target and set size. As set size increased from 3 to 7, the critical object was looked at earlier when it was semantically unrelated to the distractors, especially on target-absent trials (See Table 13 for the model output).

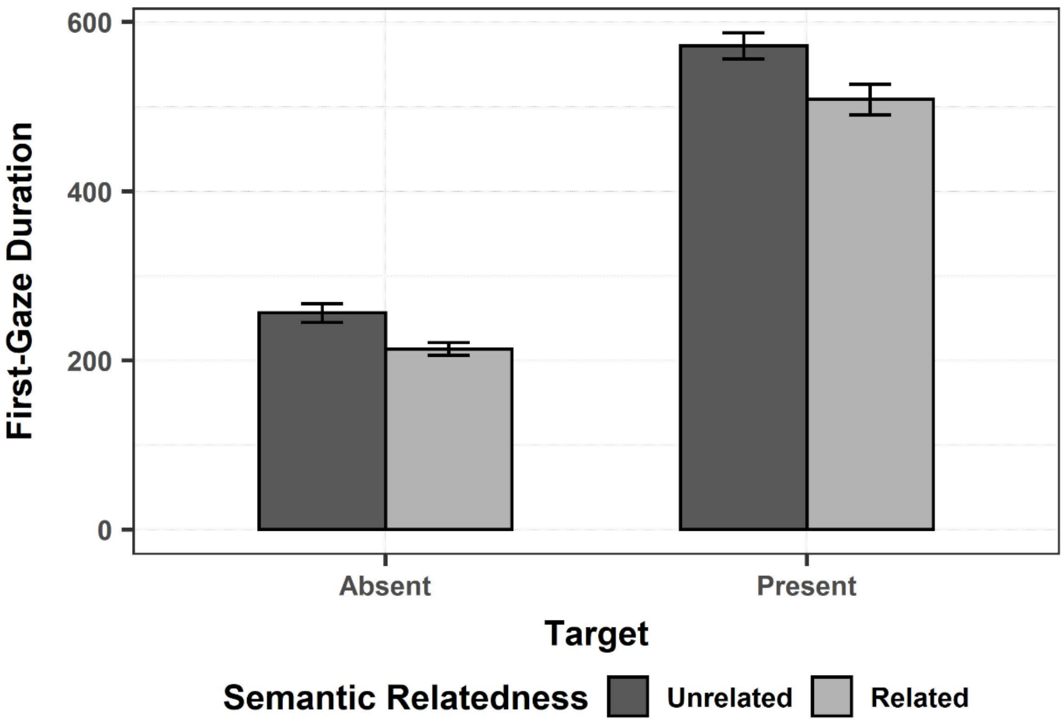


Figure 22. Mean first-gaze duration (ms) on the critical object on target-absent and -present trials (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

On the first-gaze duration (Figure 22), there was a significant main effect of target, with the critical object fixated for longer on target-present than -absent trials. There was also a significant main effect of semantic relatedness: the critical object was fixated for less time when semantically related than unrelated to the distractors (See Table 14 for the model output). Interestingly, the effects of semantic relatedness, and target, on first-gaze duration were also found when looking only at the trials in which the critical object was also the first fixated object after array onset, i.e., 985 trials: Target (absent: M = 238.93, SD = 150.04; present: M = 558.29, SD = 282.87; β = 322.29, SE = 17.75, t = 18.16, p< .001); Semantic relatedness (unrelated: M

Table 14

Linear Mixed-effects Model Output for the First-gaze Duration on the Critical Object

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
First-gaze Duration	Intercept	387.67	7.12	54.44	**< 0.001**
	Target	306.91	13.27	23.13	**< 0.001**
	Semantic Relatedness	- 51.70	8.45	- 6.12	**< 0.001**
	Visual Similarity	- 18.77	9.53	- 1.97	0.05
	Semantic Relatedness:Target	- 25.16	13.29	- 1.89	0.06
	Target:Visual Similarity	- 29.08	15.94	- 1.82	0.07

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: target (absent = -.5, present = .5), semantic relatedness (unrelated = -.5, related = .5), and visual similarity (dissimilar = -.5, similar = .5).

= 445.01, *SD* = 286.29; related: *M* = 374.09, *SD* = 271.05; *β* = - 86.44, *SE* = 15.48, *t* = - 5.58, *p*< .001). This finding contrasts with Henderson et al. (1987) who showed that a critical object receives shorter fixations only when a semantically related object is looked at before it.

3.3.3 Discussion

Data from Experiments 1 and 2 showed that a critical object was looked at earlier and for longer when it was semantically unrelated than related to the other objects in the display, both when it was the search target (target-present trials) and when it was a target's semantically related competitor (target-absent trials). Semantic relatedness effects manifested already during the very first fixation after array onset, in arrays of increasing sizes, with those on search latencies being more pronounced for target-absent trials (see Belke et al., 2008; Moores et al., 2003, for related findings).

Low-level visual saliency did not exert any influence on overt attention, in line with previous visual search studies on object arrays (e.g., Chen &

Zelinsky, 2006). Altogether, these results highlight the primary role played by object semantics in guiding overt attention in early adulthood. Less is known about how semantic information influences eye-movement control as we age, with current research providing contrasting findings about whether older adults can rely on the semantic features of objects to guide overt attention as younger adults do (Borges et al., 2020; Boucart et al., 2014). Experiment 3 sheds new light on this issue.

3.4 Experiment 3

Experiment 3 aimed to provide new evidence on the age-related differences in semantic guidance of overt attention, and thus in the extra-foveal processing of object semantic information, by monitoring the eye movements of younger and older adults performing a visual search task on object arrays.

The two groups performed the same search task as in Experiments 1 and 2, and asked to search for a cued target object in arrays with one critical object and four semantically homogeneous distractor objects. The critical object was either the search target (present trials), or a target's semantically related competitor (absent trials), either salient or non-salient, and either semantically related or unrelated to the distractors.

If older adults can use object semantic information to allocate overt attention during search, as efficiently as younger adults (Borges et al., 2020), then semantic relatedness should affect both measures of attentional capture and processing, similarly in both age groups. Specifically, the critical object should be looked at earlier and for longer when semantically unrelated than related to distractors in the array, in line with the results found in Experiments 1 and 2. Instead, if older adults do not rely on object semantics to guide search as younger adults do (Boucart et al., 2014), then evidence of semantic relatedness effects should be reduced in older age.

3.4.1 Methods

3.4.1.1 Participants

Thirty-two younger adults (26 women), students at the University of Edinburgh and aged between 18 and 30 years (*M* = 21.81, *SD* = 3.02), as well as 32 older adults (16 women), recruited via the University of Edinburgh's volunteer panel and aged between 68 and 85 years (*M* = 72.91, *SD* = 4.45), participated in the experiment for a £5.00 honorarium. The two groups did not differ significantly in years of education (younger: *M* = 15.62, *SD* = 1.64; older: *M* = 15.03, *SD* = 2.38; *t*(55.1) = -1.16, *p* = .25). All participants were native English speakers and had a normal or corrected-to-normal vision, with no history of neurological and/or psychiatric illness. Participants were screened for mild cognitive impairment using the Montreal Cognitive Assessment Test, MoCA, (Nasreddine et al., 2005). The MoCA scores of the younger group (*M* = 28.84, *SD* = .95) were significantly higher than those of the older one (*M* = 27.81, *SD* = 1.31), *t*(56.75) = - 3.61, *p* = .001; however, all participants performed above the cut-off score of 26 (scores of 25 or below indicate impairment).

3.4.1.2 Design

A 2x2x2x2 mixed factorial design was used with Semantic Relatedness (unrelated, related), Visual Saliency (non-salient, salient), and Target (absent, present) as within-participants variables, and Group (younger, older) as between-participants variable.

3.4.1.3 Stimuli

A total of 160 five-object experimental arrays were used as visual contexts for the search task, of which the 128 five-object arrays used in Experiments 1 and 2 plus additional 32 five-object arrays constructed by crossing the visual saliency and the semantic relatedness of 8 new critical objects (i.e., 8 * 4), which allowed me to increase the number of observations for each participant; see Supplemental Materials A for the miniatures of the 32 new experimental arrays.

There were also 40 five-object filler arrays, the 32 five-object arrays from Experiments 1 and 2, plus 8 new five-object filler arrays, containing objects that did not appear in the experimental arrays. The arrays were presented at the same resolution of 1024 x 768 pixels, and at the same viewing distance of 82 cm, as in Experiments 1 and 2. Each participant saw the same 40 fillers and 40 unique experimental arrays, which were counterbalanced across the conditions of visual saliency, semantic relatedness, and target using a Latin square rotation. In the target-present condition, the target name cued the critical object as the search target. In the target-absent condition, the cue word did not refer to any object in the arrays, but it was either semantically related to the critical object depicted in the arrays and unrelated to all other semantically homogeneous distractor objects (*M* = .03, *SD* = .11), or semantically related to all objects (*M* = .30, *SD* = .21), $t(39) = 7.02$, $p<.001$, Cohen's $d = 1.11$ (see Supplemental Materials C for the list of target-present and target-absent experimental trials for the 8 new critical objects).

3.4.1.4 Procedure

The procedure was the same as for Experiments 1 and 2 with the exception that the presentation of the object array was triggered by the experimenter pressing the "F" key, on his keyboard, as soon as participants looked at the central fixation cross; and that the number response was recorded by the experimenter who typed in, on his keyboard, the number matching participants' verbal response. Prior to data collection, I assumed that using a gaze-contingent window in an experiment involving adults up to 85 years of age could have slowed down its execution. Moreover, I assumed that older participants could have had problems with looking at the numeric keypad to provide the number response without moving their heads (as young participants were asked to do in Experiments 1 and 2), which would have required the repetition of the calibration and validation procedure. Thus, to avoid the potential lengthening of the experimental session and reduce participants' discomfort, the experimenter was given more control over the experimental procedure.

Each participant completed 4 practice trials and 80 randomized trials (40 experimental and 40 filler trials). The experimental session lasted approximately 30 minutes.

3.4.2 Analyses

The dependent variables measured were the same as those of Experiments 1 and 2, with the exception that the dwell time on the critical object, instead of the first-gaze duration, served as a measure of fixation processing (See Chapter 2 for more details about the dependent variables). The time-dependent measures, i.e., response time and search latency, were z-scored to account for the general slowing effect associated with ageing (Faust et al., 1999). I analysed the data from the 2,560 experimental trials only (i.e., 40 trials x 64 participants). Of these trials, 175 trials were discarded because of machine error (no eye movement was recorded). On the remaining trials (2,385), I analysed the response accuracy. The response time was computed on accurate trials only (2,250), whereas eye-movement measures were computed only on accurate trials in which the critical object was fixated at least once (2,175). The fixed effects considered in the models, centred to reduce co-linearity, were: Semantic Relatedness (Unrelated = -.5, Related = .5), Visual Saliency (Non-salient = -.5, Salient = .5), Target (Absent = -.5, Present = .5), Group (Younger = -.5, Older = .5), and Visual Similarity (Dissimilar = -.5, Similar = .5), whereas the random variables included, both as intercepts and slopes, were Participant (64) and Item (160).

3.4.3 Results

As for Experiments 1 and 2, visual saliency was never included, as a significant main effect, in any best-fitting model on any of the measures analysed in Experiment 3.

3.4.3.1 Accuracy and response time

On response accuracy, there were significant main effects of target and group, whereby accuracy was higher in target-absent (M = .95, SD = .21) than -present trials (M = .93, SD = .25), β = - 1.93, SE = .60, z = - 3.22, p = .001; and for the younger (M = .96, SD = .19) than the older group (M = .92, SD = .27), β = - 1.01, SE = .29, z = - 3.46, p< .001.

When looking at standardised response times (Figure 23), I found a significant main effect of target, with faster response times on target-present than-absent trials. I also found a significant main effect of visual similarity, with faster responses when the critical object and distractors were visually dissimilar than similar. Also, there was a significant main effect of semantic relatedness, whereby search responses were faster when the critical object was semantically unrelated than related to the distractors. This was especially the case on target-absent than -present trials (for the significant two-way interaction of semantic relatedness and target). There was no significant main effect of group, nor a significant interaction with the other variables included in the model (See Table 15 for the model output).

In the analysis of raw scores (Figure 23), the significant main effects of

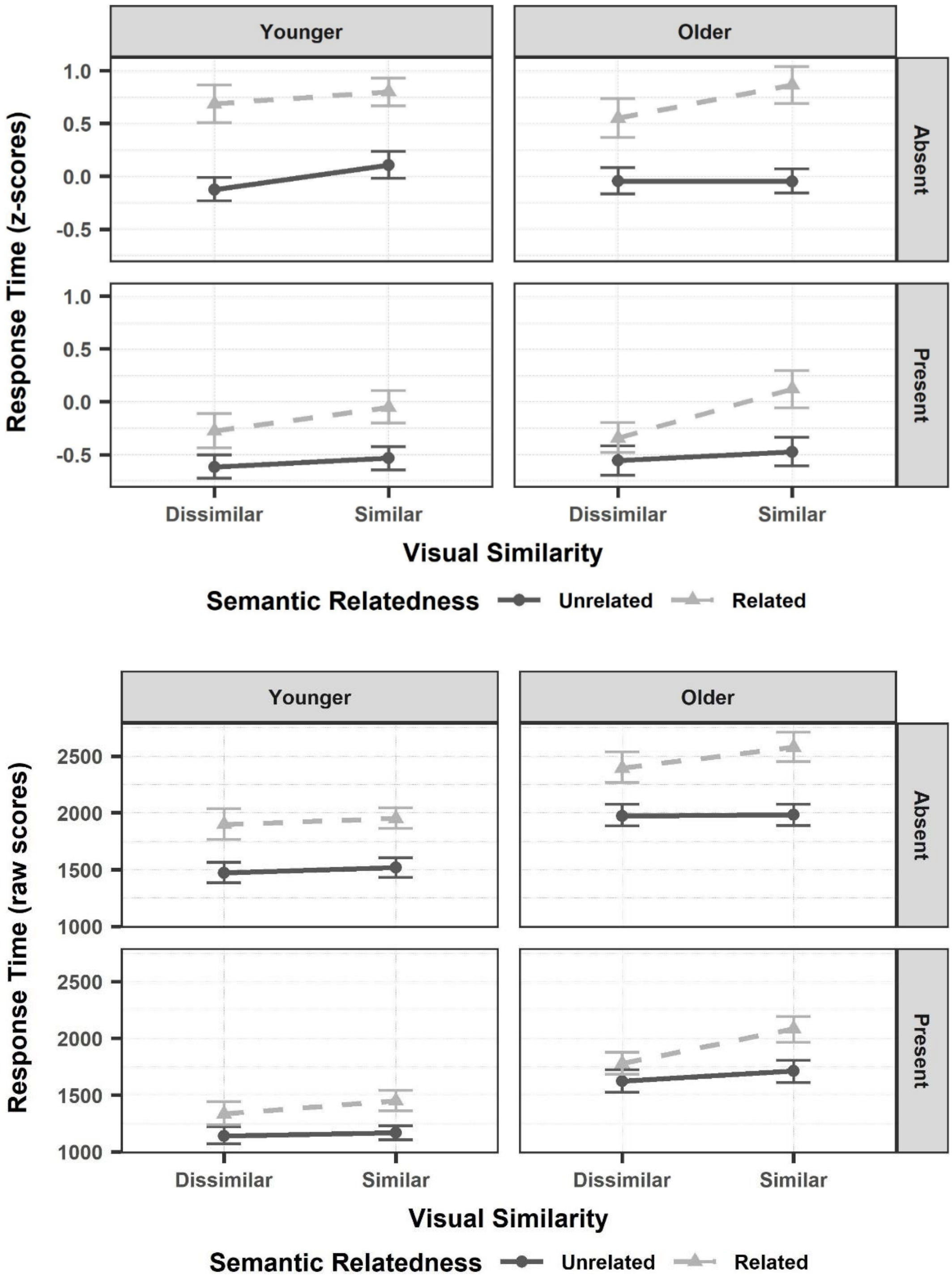


Figure 23. Mean response time (z-scores, top; raw scores, ms, bottom) for the younger (left panel) and the older group (right panel), on target-present and -absent trials, arranged over the rows of the panels, with the two levels of visual similarity (dissimilar, similar) on the x-axis. The semantic relatedness of the critical object is marked using line types and colour (unrelated: dark grey, solid line; related: light grey, dashed line). Error bars represent 95% confidence intervals around the mean.

Table 15

Linear Mixed-effects Model Output for Response Time

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
Response Time (z-scores)	Intercept	0.02	0.03	0.45	0.65
	Group	0.02	0.03	0.75	0.46
	Target	- 0.68	0.07	- 10.09	**< 0.001**
	Semantic Relatedness	0.60	0.07	8.73	**< 0.001**
	Visual Similarity	0.19	0.07	2.78	**0.006**
	Group:Target	0.08	0.10	0.73	0.47
	Group:Semantic Relatedness	0.03	0.06	0.49	0.63
	Group:Visual Similarity	0.04	0.06	0.62	0.54
	Semantic Relatedness:Target	- 0.33	0.10	- 3.21	**0.002**
	Group:Semantic Relatedness:Target	- 0.02	0.12	- 0.18	0.86
Response Time (raw scores)	Intercept	1751.21	37.16	47.130	**< 0.001**
	Target	- 432.92	49.81	- 8.69	**< 0.001**
	Group	531.01	59.38	8.94	**< 0.001**
	Semantic Relatedness	372.84	42.94	8.68	**< 0.001**
	Visual Similarity	104.06	42.12	2.47	**0.01**
	Semantic Relatedness:Target	- 217.66	68.92	- 3.16	**0.002**
	Group:Semantic Relatedness	78.88	45.74	1.73	0.09
	Group:Semantic Relatedness:Visual Similarity	230.89	94.23	2.45	**0.02**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Group (younger = -.5, older = .5), Target (absent = -.5, present = .5), Semantic Relatedness (unrelated = -.5, related = .5), and Visual Similarity (dissimilar = -.5, similar = .5).

target, visual similarity, and semantic relatedness were replicated, as well as, the significant two-way interaction between semantic relatedness and target. I also found a significant main effect of group, whereby younger adults responded faster than older adults; and a significant three-way interaction between semantic relatedness, visual similarity and group, with slower response times when the critical object was semantically related and visually similar to the distractors, especially for older adults (Table 15).

3.4.3.2 Probability of immediate fixation, search latency, and dwell time

On the probability of immediate fixation (Figure 24), I found significant main effects of group and semantic relatedness. The probability of looking at the critical object on the first fixation after array onset was higher for younger than older adults, and when it was semantically unrelated than related to the distractors. I also found a significant main effect of target, whereby the probability of immediate fixation to the critical object was higher on target-present than -absent trials. This was especially the case for younger than older adults (for the significant two- way interaction between target and group) (Refer to Table 16 for the model output). Critically, Figure 24 shows evidence of semantic relatedness effect on early overt attention for the younger, but not for the older, group. However, Table 16 lists the interaction term of semantic relatedness and group as non-significant. I thus decided to perform a follow-up analysis on the subset of data for younger and older participants, separately. I found a significant main effect of semantic relatedness on the probability of immediate fixation for the younger (unrelated: M = .32, SD = .47; related: M = .21, SD = .41; β = - .70, SE = .26, z = - 2.72, p = .007), but not the older group (unrelated: M = .19, SD = .39; related: M = .15, SD = .36; β = - .35, SE = .34, z = - 1.03, p = .30). It is conceivable that the interaction term of semantic relatedness and group did not reach statistical significance in the first place because of the large standard deviations of the samples.

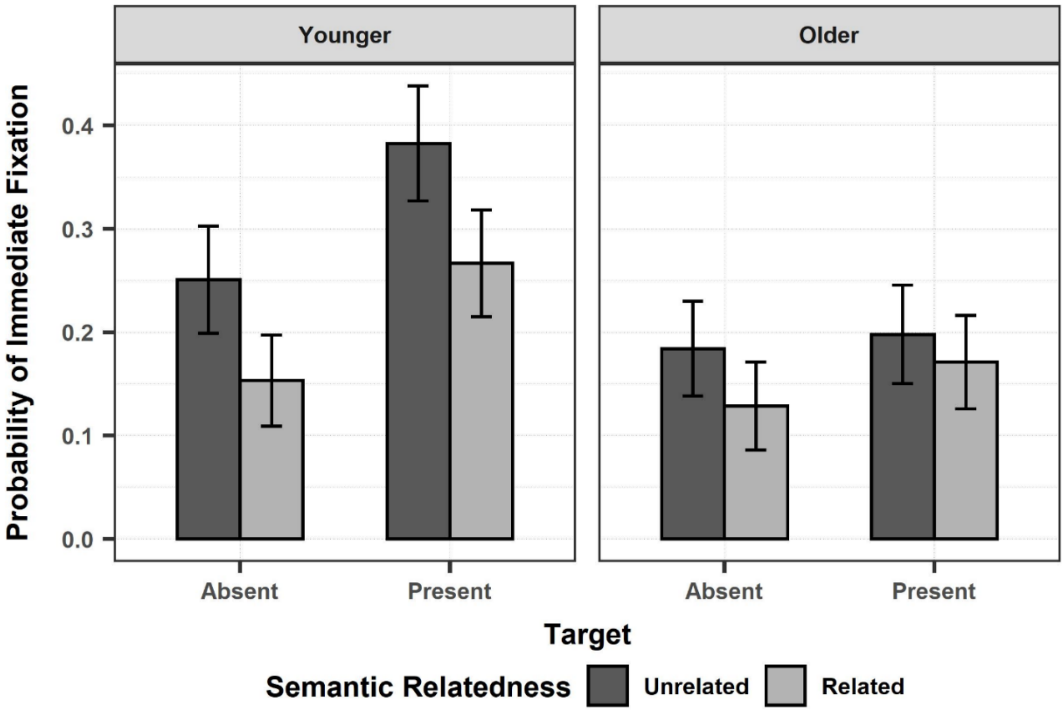


Figure 24. Mean probability of immediate fixation to the critical object (proportions) for the younger (left panel) and older group (right panel), on target-present and -absent trials (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 16

Generalized Linear Mixed-effects Model Output for the Probability of Immediate Fixation to the Critical Object

Dependent Variable	Predictor	β	SE	z-value	Pr (> | z |)
Probability of Immediate Fixation	Intercept	- 1.73	0.13	- 13.44	**< 0.001**
	Target	0.53	0.15	3.57	**< 0.001**
	Group	- 0.69	0.15	- 4.60	**< 0.001**
	Semantic Relatedness	- 0.58	0.24	- 2.37	**0.02**
	Group:Target	- 0.55	0.25	- 2.24	**0.03**
	Group:Semantic Relatedness	0.40	0.33	1.24	0.21

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Target (absent = -.5, present = .5), Group (younger = -.5, older = .5), and Semantic Relatedness (unrelated = -.5, related = .5).

On the standardised search latency (Figure 25), I found a significant main effect of target. The critical object was fixated earlier on target-present than -absent trials. There was also a significant main effect of semantic relatedness, whereby the critical object was looked at earlier when it was semantically unrelated than related to the distractors. This was especially the case for target-absent than -present trials (for the significant two-way interaction of semantic relatedness and target). There was no significant main effect of group, nor a significant interaction with the other variables included in the model (See Table 17 for the model output). In the analysis of raw scores (Figure 25), I found significant main effects of target and semantic relatedness, and a significant interaction between the two, thus replicating the findings on z-scores. Moreover, I found a significant main effect of group, with the critical object looked at earlier by younger than older adults (Table 17).

On dwell times (Figure 26), I found a significant main effect of target, with longer dwell times on target-present than -absent trials. I also found a significant main effect of semantic relatedness, whereby dwell times were longer when the critical object was semantically unrelated than related to the distractors. Finally, there was a significant main effect of visual similarity, with longer dwell times for the critical object when dissimilar than similar to the distractors (Refer to Table 18 for the model output).

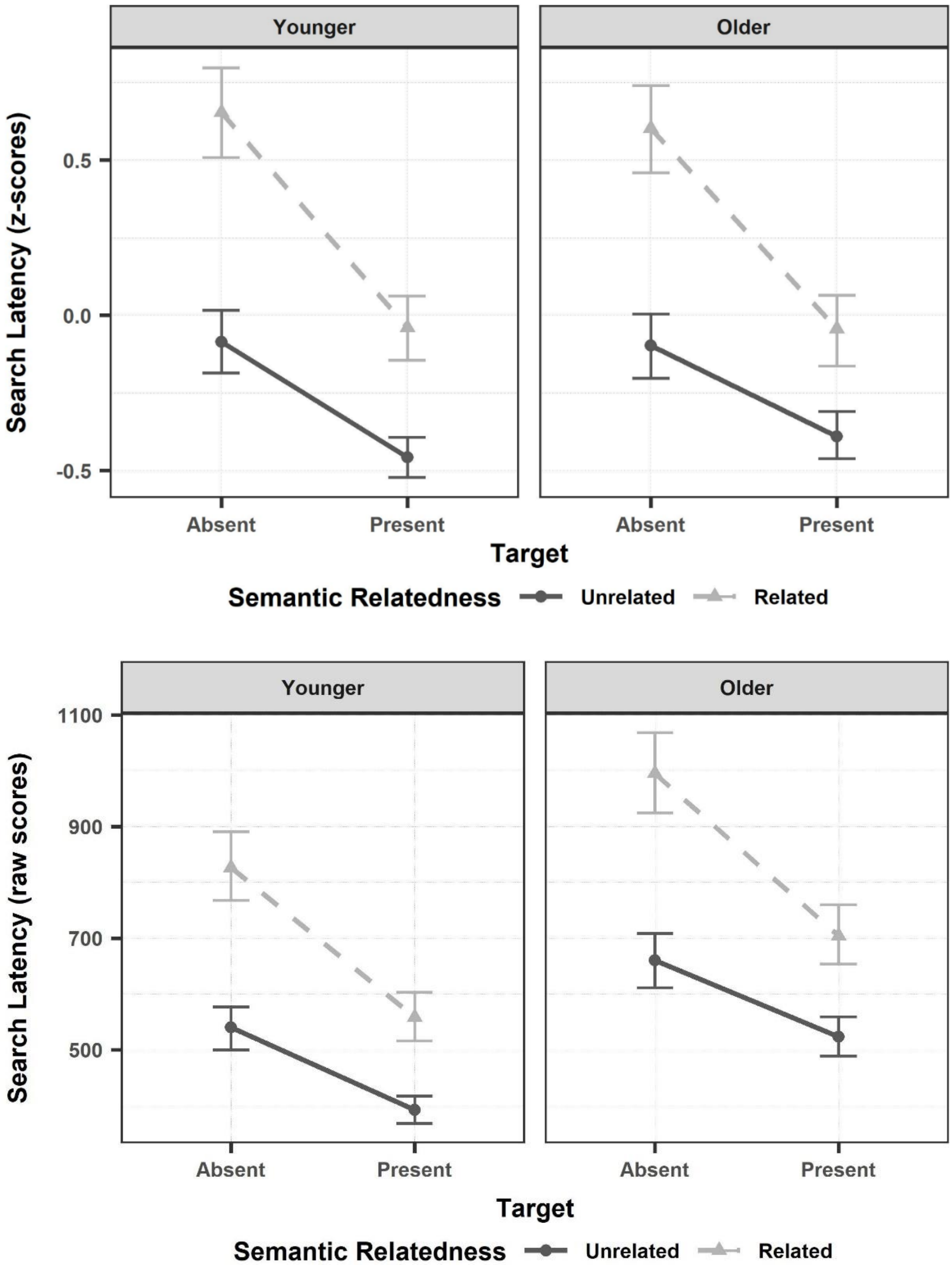


Figure 25. Mean search latency (z-scores, top; raw scores, ms, bottom) on the critical object for the younger (left panel) and older group (right panel), on target-present and -absent trials (on the x-axis), with the semantic relatedness of the critical object marked using line types and colour (unrelated: dark grey, solid line; related: light grey, dashed line). Error bars represent 95% confidence intervals around the mean.

Table 17

Linear Mixed-effects Model Output for the Search Latency on the Critical Object

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
Search Latency (z-scores)	Intercept	0.01	0.04	0.19	0.84
	Group	0.01	0.03	0.16	0.87
	Target	- 0.48	0.05	- 9.18	**< 0.001**
	Semantic Relatedness	0.55	0.07	7.62	**< 0.001**
	Group:Target	0.05	0.07	0.73	0.46
	Group:Semantic Relatedness	- 0.06	0.08	- 0.80	0.43
	Semantic Relatedness:Target	- 0.32	0.10	- 3.07	**0.003**
	Group:Semantic Relatedness:Target	- 0.04	0.14	- 0.31	0.76
Search Latency (raw scores)	Intercept	643.87	16.20	39.74	**< 0.001**
	Target	- 201.53	23.25	- 8.67	**< 0.001**
	Semantic Relatedness	233.86	31.22	7.49	**< 0.001**
	Group	137.14	18.77	7.31	**< 0.001**
	Visual Similarity	49.94	28.33	1.76	0.08
	Semantic Relatedness:Target	- 132.43	46.47	- 2.85	**0.005**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Group (younger = -.5, older = .5), Target (absent = -.5, present = .5), Semantic Relatedness (unrelated = -.5, related = .5), and Visual Similarity (dissimilar = -.5, similar = .5).

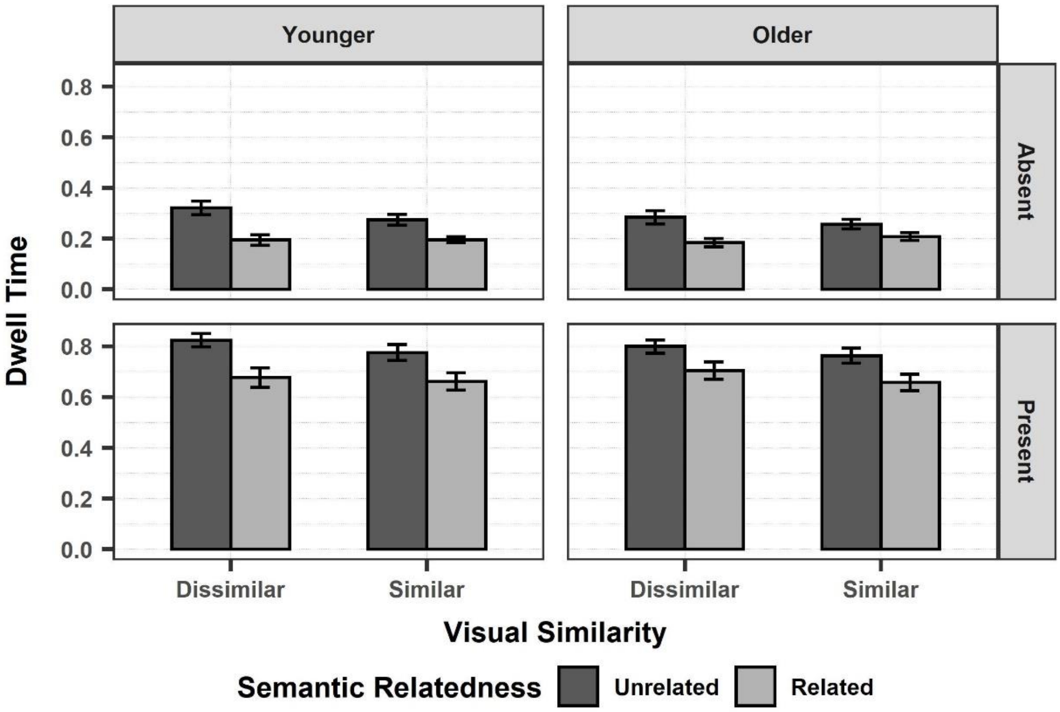


Figure 26. Mean dwell time (proportions) on the critical object for the younger (left panel) and older group (right panel), on target-present and -absent trials, arranged over the rows of the panels, with the two levels of visual similarity (dissimilar, similar) on the x-axis, in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 18

Linear Mixed-effects Model Output for the Dwell Time on the Critical Object

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
Dwell Time	Intercept	0.49	0.01	68.80	**< 0.001**
	Target	0.49	0.01	38.23	**< 0.001**
	Semantic Relatedness	- 0.10	0.01	- 9.61	**< 0.001**
	Visual Similarity	- 0.02	0.01	- 2.16	**0.03**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Target (absent = -.5, present = .5), Semantic Relatedness (unrelated = -.5, related = .5), and Visual Similarity (dissimilar = -.5, similar = .5).

3.4.4 Discussion

Standardized response time and search latency data showed that the critical object was overall found and looked at earlier when it was semantically unrelated than related to the distractors, with no difference among the age groups. Critically, data on the probability of immediate fixation, showed that semantic information guided early overt attention in younger, but not older adults. These findings suggest that the extra-foveal semantic capture of attention is preserved in older adults during search on object arrays (as during search in naturalistic scenes, Borges et al., 2020). Arguably, in line with the Salthouse's processing speed-theory (Salthouse, 1996, 2012), ageing would increase the time needed to access object semantic information in extra-foveal vision, thus explaining the absence of semantic relatedness effects on initial eye movements in older adults.

Object-to-object semantic relationships also affected eye-movement measures of fixation processing, i.e., dwell time, similarly in both groups with the critical object looked at for longer when it was semantically unrelated than related to the distractors.

Finally, in line with Experiments 1 and 2, I found effects of low-level visual saliency neither on measures of extra-foveal attentional capture, nor on measures of fixation processing.

3.5 General discussion

The current chapter examined the influence of object semantic information on the allocation of overt attention, as well as its temporal dynamics, during a visual search task. In my task, participants were cued with a target to search in object arrays which displayed a critical object and distractor objects. The critical object was either the search target (present trials), or a target's semantically related competitor (absent trials), either salient or non-salient, and it was either semantically related or unrelated to the distractors, which were always semantically related to each other.

The first two experiments had young participants performing the search task on target-absent (Experiment 1) and target-present (Experiment 2) object arrays of different sizes. I found that young adults were more likely to direct the very first fixation after the onset of the object array, and overall inspect for the first time earlier, the critical object when it was semantically unrelated than related to the distractors, especially on target-absent trials. These findings clearly indicate that object semantic information can be extracted in extra-foveal vision, as early as the onset of the visual context, to guide early overt attention. Moores et al. (2003) and Belke et al. (2008) had also reported semantic relatedness effects on initial eye movements during search. However, these earlier studies have been criticised by Daffron and Davis (2016) who suggested that the effects of semantic relatedness might have been confounded by the repeated presentation of the visual stimuli to the participants. Thus, overt attention might have been biased by remembered visual features of the objects, rather than by their semantic features. The same criticism cannot be raised here, as each object was never presented more than once to each participant. In contrast with de Groot et al. (2016) and Nuthmann et al. (2019) who found a stronger effect of visual similarity on early overt attention compared to semantic relatedness, I did not find any significant main effect of visual similarity on eye-movement behaviour. I believe that my experimental design, with all the distractors semantically related among each other, may have boosted the guidance of overt attention exerted by object semantic features over that of visual features. Nevertheless, I observed significant interactions between visual similarity and semantic relatedness on response times and search latencies. These results seem to suggest that, as visual search unfolds, the visual similarity between objects is accessed to refine the ongoing semantic guidance and optimises visual search. This suggestion is strengthened by the evidence that the effect of semantic relatedness on search guidance was weaker on target-present than -absent trials. When the target is present, participants might rely more on visual information to facilitate search, thus reducing the effect of semantic relatedness on eye movements (Huettig & Altmann, 2005; Huettig & Mcqueen, 2007).

My results also seem to suggest that some parallel processing may occur (Buetti, Cronin, Madison, Wang, & Lleras, 2016), but as semantic information may be only partially acquired in extra-foveal vision (Gordon, 2004), such processing may be limited in nature. Indeed, if the semantics of all objects are processed in parallel across the visual field, i.e., regardless of the number of distractor objects, then we should observe an identical processing advantage of the critical object when semantically unrelated than related to the semantically homogenous distractors. That is, my data should have shown, for example, the same immediate probability that the critical object is looked at first across arrays of increasing size when unrelated to the distractor objects, i.e., a canonical “pop-out” effect. I observed instead that the probability of immediate fixation to the critical object decreases with the increasing of the set size for both semantically unrelated and related critical objects. This finding would be difficult to account for in terms of full parallel processing, as we would have to assume that the processing of high-level semantic information of all objects should be completed immediately after the onset of the array. Nevertheless, if observers only processed in extra-foveal vision the semantics of just one object, i.e., serial processing, then the prioritization of a semantically unrelated object should be substantially reduced (and perhaps become indistinguishable) compared to a semantically related object as the number of semantically homogenous distractors increases. Instead, even if the identification of the critical object became harder as the number of distractors increased, a semantically unrelated object maintained an advantage to be prioritized over a semantically related object. I also conducted a further analysis of the latency to generate the first saccade after the onset of the object array, which reflects the time to select the first target candidate (Malcolm & Henderson, 2009, 2010). This analysis shows no effect of set size, whereby the time needed to make the first saccade did not increase as the number of the objects in the array increased from 3 (M = 156.28, SD = 56.37) to 5 (M = 147.01, SD = 47.33)(β = - 8.80, SE = 5.86, $t = -1.50$, $p = .14$), and to 7 ($M = 154.27$, $SD = 55.51$)($\beta = -2.41$, SE = 5.86, $t = -.41$, $p = .68$). This finding also counters a serial processing account of object semantics. Indeed, if participants had serially attended, covertly or pre-attentively, to all the objects in the array prior to making the first fixation, then the first saccade should have occurred later for arrays of increasing size.

Semantic processing also mediated the time spent looking at the critical object when it was foveated for the first time. In particular, I found that the critical object was fixated for the first time less when it was semantically related than unrelated to the distractors, also when restricting the analysis to the trials where the critical object was the first object fixated. This finding implies that the semantic information of more than a single object was accessed in extra-foveal vision during the very first fixation, in line with previous research on object arrays (Auckland, Cave, & Donnelly, 2007) or naturalistic scenes (Davenport, 2007) and affected early overt attention. Indeed, only if the semantics of the objects are immediately available at the onset of the array, we can observe effects of semantic relatedness on the duration of the very first fixation. The foveal processing of the critical object might have been facilitated by the extra-foveal analysis of semantically related objects (object-to-object priming, Henderson et al., 1987) or slowed down by the semantic unrelatedness of the distractors (i.e., more time would be needed to integrate the critical object in a context of semantically unrelated objects, e.g., Bonitz & Gordon, 2008; Henderson et al., 1999; Loftus & Mackworth, 1978; Võ & Henderson, 2009).

Evidence of extra-foveal capture of initial eye movements of young adults was replicated in Experiment 3, but was not found for healthy older adults, as showed by the analysis of the probability of immediate fixation. However, on standardised search latency, I found that object semantics contributed to guiding overt attention similarly in younger and older participants. Throughout the trial, the critical object was located earlier when it was semantically unrelated than related to the distractors, especially in target-absent trials, in both the younger and older group, with no difference among them, i.e., no significant semantic relatedness x group interaction, in line with recent visual search studies in naturalistic scenes (Borges et al., 2020). Altogether, these findings indicate that healthy older adults use extra-foveal semantic information as efficiently as young adults do to guide overt attention, but they might require more time to process the semantic features of objects in extra-foveal vision, presumably as a consequence of the general slowing of cognitive processes associated to ageing (Salthouse, 1996, 2012).

Age-related differences were also found on measures of foveal processing, i.e., dwell times. The proportion of time spent looking at the critical object was shorter when it was semantically related than unrelated to the distractors, in both younger and older participants.

In sum, Chapter 3 shows that the semantic features of objects are accessed in extra-foveal vision to guide overt attention during a search task, in both younger and older adults. Evidence of semantic relatedness effects on initial eye movements in younger adults demonstrates that object semantics can be processed in extra-foveal vision as early as at the onset of the visual context. Extra-foveal semantic processing is preserved in older adults to a degree sufficient to affect the allocation of overt attention during search, although there might be age-related changes in the time course of such processing. This last finding is particularly relevant given the well-documented impairment in semantic processing associated with pathological ageing, i.e., AD. However, the extent to which the processing of semantic information is impaired in AD patients is under debate, and its effects on the guidance of overt attention are still unknown. This gap is addressed in the following chapter, where I used the same visual search task to examine the influence of semantic information on eye-movement control in AD patients and healthy age-matched controls.

4 Semantic guidance of overt attention in Alzheimer’s disease during search

4.1 Introduction

A hallmark of AD and degenerative cognitive deficits leading to AD (Mild Cognitive Impairment, MCI) is their detrimental impact on semantic memory (Daum et al., 1996; Martin & Fedio, 1983; Mulatti et al., 2014). AD patients typically underperform in tasks using verbal stimuli (i.e., words) and requiring controlled access to semantic information from memory, e.g., category fluency (Salmon et al., 1999), word-to-picture matching (Adlam et al., 2006), and object naming (Holmes et al., 2006). Critically, in tasks using non-verbal stimuli (i.e., pictures), and/or those which can be performed more automatically (e.g., semantic priming), AD patients show preserved semantic abilities (Ally, Gold, et al., 2009; Chertkow et al., 1994; Hernández et al., 2008).

Although these findings suggest that AD might determine a selective impairment in the explicit access and intentional retrieval of semantic knowledge rather than its generalised loss, the nature of the semantic impairment associated to AD is still to be understood. This chapter addresses this gap with an eye-tracking experiment (Experiment 4) where I investigate whether object semantic processing is impaired or preserved in AD patients by examining whether it implicitly mediates the allocation of overt attention during a search task.

4.2 Experiment 4

Experiment 4 used the same experimental paradigm as the experiments in the previous chapter to examine the influence of object semantics on eye-movement behaviour of AD patients and age-matched healthy controls. Participants were presented with the name of a target to search in arrays comprising a critical object and semantically homogeneous distractor objects. The target name cued attention towards the critical object as the search target (target-present trials) or as target semantically related competitor (target-absent trials). The critical object was either semantically related or unrelated to the distractors, and either salient or non-salient.

I examined both measures of extra-foveal attentional capture, i.e., probability of immediate fixation and search latency, and of foveal processing, i.e., dwell time. Three possible outcomes could emerge from the AD patients' performance: a) semantic information is processed, both in the extra-fovea and the fovea, similarly by AD patients and healthy age-matched controls; hence the critical object would be looked at earlier, and once fixated, for longer when semantically unrelated than related to the distractors; b) semantic information cannot be processed by AD patients in extra-fovea (e.g., due to a deficit in extra-foveal visual processing; Boucart et al., 2014; Rösler et al., 2005), but foveal processing is intact; hence when the critical object is semantically unrelated to the distractors, it would be looked at for longer, but not earlier, compared to when it is semantically related to them; c) semantic processing of visual information is overall disrupted in AD patients, hence there would be no evidence of semantic relatedness effects in any eye-movement measure analysed.

4.2.1 Methods

4.2.1.1 Participants

A group of 20 patients with a diagnosis of mild to moderate AD (14 women) and a group of 20 healthy matched controls (9 women) took part in the experiment. Participants were native Italian speakers recruited from the Neurological and Stroke Unit at CTO Hospital, Naples (15 patients and 10 controls) and the Alzheimer's Disease Italian Association AIMA Campania (5 patients and 10 controls). The diagnosis of AD was based on family and medical history interview, and neuroimaging evidence (available for 16 out of 20 patients; MRI and PET: 3 patients, MRI and CAT: 1 patient, MRI only: 8 patients, PET only: 4 patients), according to the NINCDS-180 ADRDA criteria (McKhann et al., 1984), as well as on neuropsychological testing, including the Italian version of the mini-mental state examination (MMSE, Folstein, Folstein, & McHugh, 1975; Frisoni, Rozzini, Bianchetti, & Trabucchi, 1993), the frontal assessment battery (FAB, Dubois, Slachevsky, Litvan, & Pillon, 2000; Iavarone et al., 2004), the Rey's auditory verbal learning test (Ricci, Graef, Blundo, & Miller, 2012), word fluency (Costa et al., 2014), Raven's coloured progressive matrices (Ambra et al., 2016), freehand copying of drawings, and copying of drawings with landmarks (Gainotti, Miceli, & Caltagirone, 1977). Eighteen AD patients, as well as all the healthy controls, were also administered the Albert's test (Fullerton, Mcsherry, & Stout, 1986), the word-nonword reading test and the object naming test from the Esame neuropsicologico per l'afasia (ENPA, Capasso & Miceli, 2001), and the digit span forwards from the Wechsler adult intelligence scale (WAIS-IV, Wechsler, 2008). Inclusion criteria for both AD patients and healthy controls were: 1) MMSE raw score ≥ 16; 2) between 50 and 90 years of age; 3) no less than 3 years of schooling; 4) normal or corrected-to-normal vision with no history of eye surgery; 5) no history of neurological (other than AD) and/or psychiatric disorders; 6) no history of alcohol or substance abuse and/or use of medications likely to affect cognitive functioning; 7) able to understand the instructions and perform the task; 8) no omission errors on the Albert's test. The two groups were matched on age and years of education, whereas the MMSE scores of the AD group were significantly lower than those of the control group. Moreover, the performances of the two groups did not differ significantly on object naming and word reading, whereas the scores of the AD group were significantly lower than those of the controls on nonword reading and the digit span forwards (see Table 19 and Table 20 for the descriptive statistics of the sample).

4.2.1.2 Design

A 2x2x2x2 mixed factorial design was used with Semantic Relatedness (unrelated, related), Visual Saliency (non-salient, salient), and Target (absent, present) as within-participants variables, and Group (control, AD) as a between-participants variable.

Table 19

Means, Standard Deviations (in parenthesis), t-values, and p-values for the Demographic Features and the Scores on MMSE, Word-nonword Reading Test, Object Naming Test, and Digit Span Forwards.

Variables		AD	Control	t-value	p-value
Age (in years)		71.15 (8.50)	69.35 (5.52)	0.79	0.43
Education (in years)		8.90 (4.29)	10.50 (4.37)	- 1.17	0.25
MMSE	Raw	20.85 (2.68)	28.40 (1.35)	- 11.24	**< 0.001**
	Corrected	21.46 (2.37)	28.86 (2.08)	- 11.36	**< 0.001**
Word Reading		9.61 (0.50)	9.85 (0.37)	- 1.66	0.11
Nonword Reading		4.44 (0.92)	4.95 (0.22)	- 2.27	**0.04**
Object Naming		9.56 (0.78)	9.85 (0.37)	- 1.46	0.16
Digit Span Forwards	Total Raw Score	6.83 (1.69)	8.15 (1.39)	- 2.61	**0.01**
	LDSF	4.83 (0.99)	5.65 (0.93)	- 2.62	**0.01**

Note. LDSF: Longest digit span forwards, i.e., the number of digits on the last trial correctly recalled (corresponding to the memory span). The word-nonword reading test, the object naming test, and the digit span forwards were administered to 18 (out of 20) AD patients, and all the controls.

Table 20

Neuropsychological Tests' Ranges, Cut-off Scores, Raw and Corrected Score Means and Standard Deviations (in parenthesis) of the AD group

Neuropsychological Test		Range	Cut-off score	Raw	Corrected
FAB		0–18	12.03	10.37 (2.09)	12.59 (2.42)
RAVLT	IR	0–75	28.53	19.90 (7.97)	25.57 (8.37)
	DR	0–15	4.69	1.15 (1.39)	2.99 (1.44)
WF		0– ...	17.35	21.4 (9.08)	24.78 (8.79)
RCPM		0–36	18.96	17.32 (5.09)	19.73 (5.44)
CD		0–12	7.18	6.32 (2.85)	6.89 (2.89)
CDL		0–70	61.85	58.53 (11.35)	59.53 (11.49)

Note. FAB: frontal assessment battery; RAVLT: Rey's auditory verbal learning test (IR, immediate recall; DR, delayed recall); WF: word fluency; RCPM: Raven's coloured progressive matrices; CD: freehand copying of drawings; CDL: copying drawings with landmarks. Corrected scores below the corresponding cut-off scores indicate impairment.

4.2.1.3 Stimuli

I used the same stimuli as those of Experiment 3 in the previous chapter, i.e., 160 five-object experimental arrays and 40 five-object filler arrays. The object arrays were presented at a resolution of 1024 x 768 pixels, at a viewing distance of 75 cm (28.43° and 22.62° of visual angle on the horizontal and on the vertical axis, respectively). The distance between the centre of the array (i.e., the starting fixation point) and the midpoint of each object was 344 pixels (9.75°), while the distance between the adjacent objects' midpoints was 404.40 pixels (11.46°). Each participant saw the same 40 fillers and 40 unique experimental arrays, which were counterbalanced across the conditions of visual saliency, semantic relatedness, and target using a Latin square rotation.

4.2.1.4 Procedure

At the beginning of each experimental session, the eye tracker was calibrated using a 9-point grid appearing on the monitor. Each trial began with a fixation cross at the centre of the display. As soon as participants looked at it, the experimenter, who was monitoring their gaze position, manually pressed the F key on his keyboard to trigger the cue word indicating the search target. The word was visible on the screen for 1,200 ms, followed by another central fixation cross for 150 ms, and then the object array. Participants received written and verbal instructions and asked to perform the task, i.e., indicate whether the target was present or not in the object array, as quickly and accurately as possible by verbally responding *sì*

(Italian for *yes*) if the target was present, or *no* if it was not. The experimenter recorded participants' responses by pressing the left or the right arrow key on his keyboard, respectively. Participants were given 5000 ms to complete the search, otherwise, a null response was logged. If participants answered *no,* the experiment progressed to the next trial. If participants answered *yes*, the object array was replaced by a number array and they were asked to verbally indicate the number matching the target location, which the experimenter recorded by typing in, on his keyboard, the number matching participants' verbal response. Each participant completed 4 practice trials and 80 randomized trials (40 experimental and 40 filler trials). If a patient could not remember the task, the experiment was stopped, and the instructions and the practice session repeated before continuing the session. The experimental session lasted approximately 45 minutes.

4.2.1.5 Apparatus and pilot study

The apparatus used for Experiment 4 differed from that of the experiments presented in the previous chapter (see Chapter 2 for more details). Prior to the experiment, a pilot study was conducted on a pool of young adults to ensure that the Gazepoint GP3 HD 150 eye-tracker used in the current experiment was able to detect semantic relatedness effects on eye movements in a comparable way as the EyeLink 1000 used in Experiments 1, 2, and 3, despite its lower sample rate.

A total of 22 participants, all students of the University of Edinburgh, took part in the pilot study in exchange for either course credits or a £3.50 honorarium. They were all native English speakers and had a normal or corrected-to-normal vision. Participants were equally divided in two groups: one group of 11 participants (9 women) performed the visual search task while their eye movements were monitored by a Gazepoint GP3 HD 150 eye-tracker, whereas the other group of 11 participants (9 women) completed the same visual search task while their eye movements were recorded using an EyeLink 1000. The two groups were matched on age (EyeLink 1000: M = 21.45, SD = 2.46; Gazepoint 150: M = 21.64, SD = 2.73; $t(19.79) = -.16$, p = .87) and years of education (EyeLink 1000: M = 16.00, SD = 1.55; Gazepoint 150: M = 16.00, SD = 1.61; $t(19.97) = 0$, p = 1).

A 2x2x2x2 mixed factorial design was used with Semantic Relatedness (unrelated, related), Visual Saliency (non-salient, salient), and Target (absent, present) as within-participants variables, and Group (EyeLink1000, Gazepoint 150) as between-participants variable. The stimulus materials and procedure for the pilot study were the same as those of Experiment 4.

The dependent variables analysed were response accuracy, and the probability of immediate fixation, search latency and dwell time on the critical object. I examined the 880 experimental trials only (i.e., 40 trials for 22 participants). Of these trials, I discarded 25 trials because of machine error (no eye movement was recorded). On the remaining trials (855), I analysed the response accuracy. The eye-movement measures were computed only on accurate trials in which the critical object was fixated at least once (712). The fixed effects considered in the models, centred to reduce co-linearity, were: Semantic Relatedness (Unrelated = -.5, Related = .5), Visual Saliency

(Non-salient = -.5, Salient = .5), Target (Absent = -.5, Present = .5), Group (EyeLink1000 = -.5, Gazepoint 150 = .5), and Visual Similarity (Dissimilar = -.5, Similar = .5), whereas the random variables included, both as intercepts and slopes, were Participant (22) and Item (160).

Response accuracy was at ceiling (target-present: M = .92, SD = .27; target-absent: M = .96, SD = .19; β = -.87, SE = .42, z = - 2.06, p< .05), and did not differ among the two groups (EyeLink 1000: M = .95, SD = .21; Gazepoint 150: M = .94, SD = .24; χ^2 = .88, p = .34; group did not significantly improve the model fit during model selection).

On the probability of immediate fixation (Figure 27), I found a significant main effect of target, whereby the probability of looking at the critical object on the first fixation after array onset was higher on target-present (M = .29, SD = .45) than target-absent trials (M = .17, SD = .38; β = .76, SE = .21, z = 3.62, p< .001). Neither semantic relatedness (unrelated: M = .25, SD = .44; related: M = .21, SD = .41; χ^2 = 1.78, p = .18) nor group (EyeLink 1000: M = .24, SD = .43; Gazepoint 150: M = .22, SD = .42; χ^2 = .29, p = .59) were retained during model selection as they did not significantly improve the model fit.

On search latency (Figure 28), there was a significant main effect of target, whereby the critical object was fixated earlier on target-present (M = 525.76, SD = 336.72) than target-absent trials (M = 711.24, SD = 423.76; β = - 174.47, SE = 25.41, t = - 6.87, p< .001). There was also a significant main effect of semantic relatedness, with the critical object looked at earlier when it was semantically unrelated (M = 510.77, SD = 284.31) than related to the

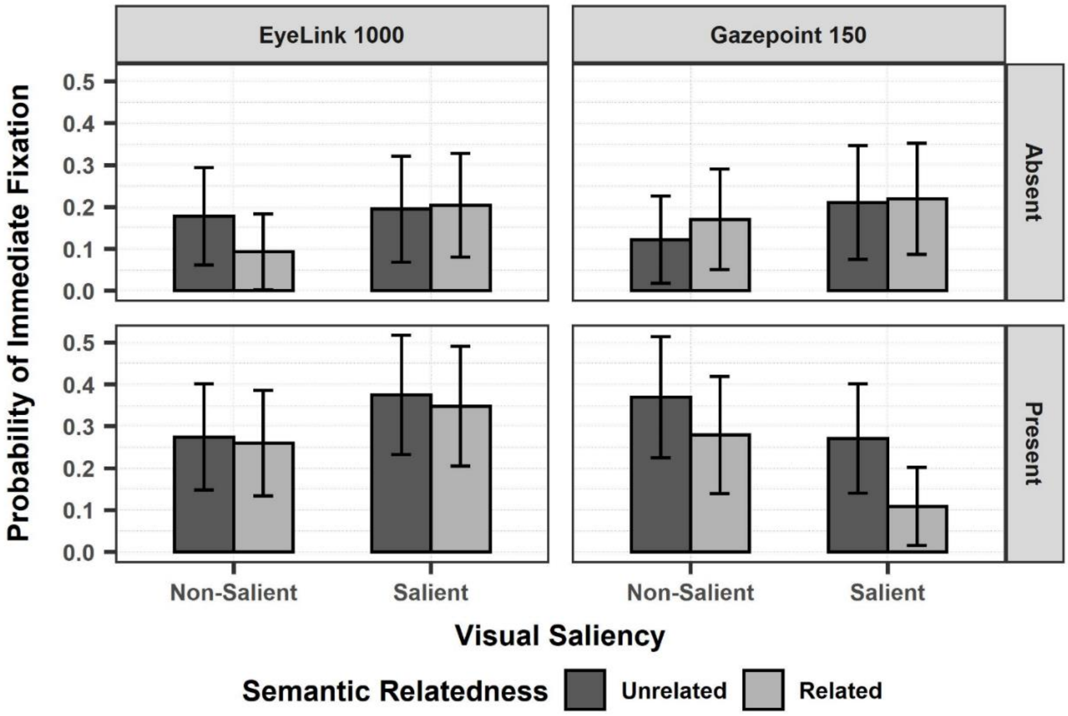


Figure 27. Mean probability of immediate fixation to the critical object (proportions) for the EyeLink 1000 (left panel) and Gazepoint 150 group (right panel) on target-present and -absent trials, arranged over the rows of the panels, with the two levels of visual saliency (non-salient, salient) on the x-axis, in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

distractors (*M* = 715.92, *SD* = 452.55; β = 197.96, *SE* = 34.87, *t* = 5.68, $p<$ .001). This was especially the case on target-absent than target-present trials (for the significant two-way interaction between semantic relatedness and target; β = -107.59, *SE* = 50.70, *t* = - 2.12, $p<$ .05). Critically, group was not retained during model selection as it did not significantly improve the model fit (EyeLink 1000: *M* = 599.35, *SD* = 414.76; Gazepoint 150: *M* = 627.12, *SD* = 363.70; χ^2 = .83, *p* = .36).

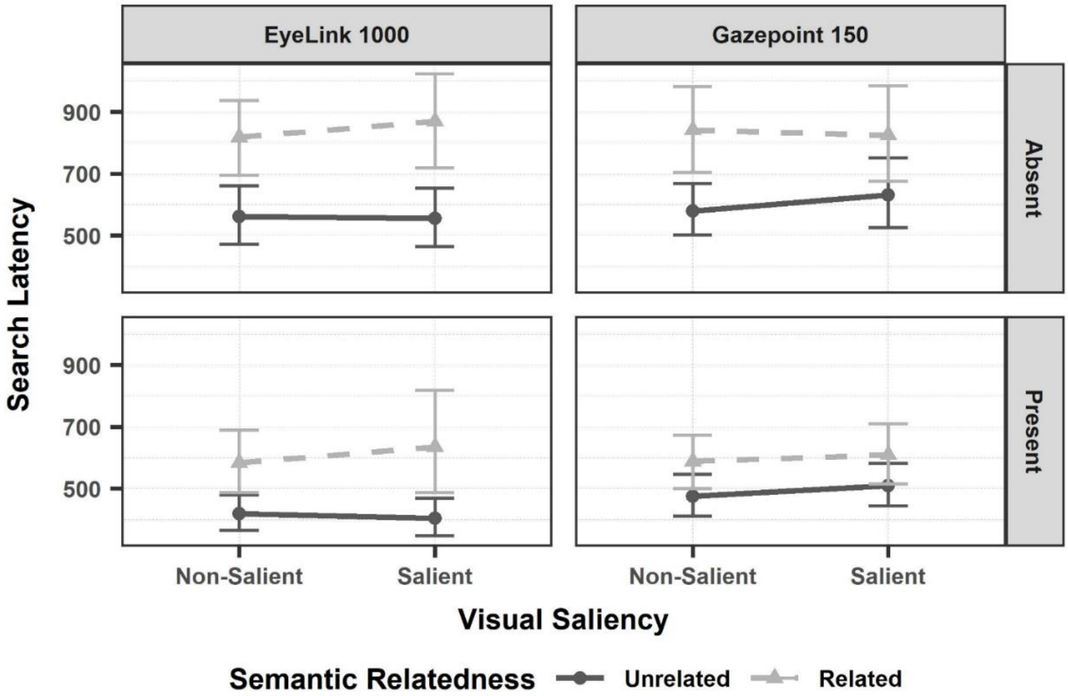


Figure 28. Mean search latency (ms) on the critical object for the EyeLink 1000 (left panel) and Gazepoint 150 group (right panel) on target-present and -absent trials, arranged over the rows of the panels, with the two levels of visual saliency (non-salient, salient) on the x-axis, and the semantic relatedness of the critical object marked using line types and colour (unrelated: dark grey, solid line; related: light grey, dashed line). Error bars represent 95% confidence intervals around the mean.

On dwell time (Figure 29), there was a significant main effect of target, with longer dwell times on target-present (M = .70, SD = .22) than -absent trials (M = .25, SD = .14; β = .44, SE = .02, t = 20.76, p< .001), and a significant main effect of semantic relatedness, whereby dwell times were longer when the critical object was semantically unrelated (M = .54, SD = .30) than related to the distractors (M = .43, SD = .28; β = -.09, SE = .01, t = -6.36, p< .001). Group did not significantly improve the model fit and was

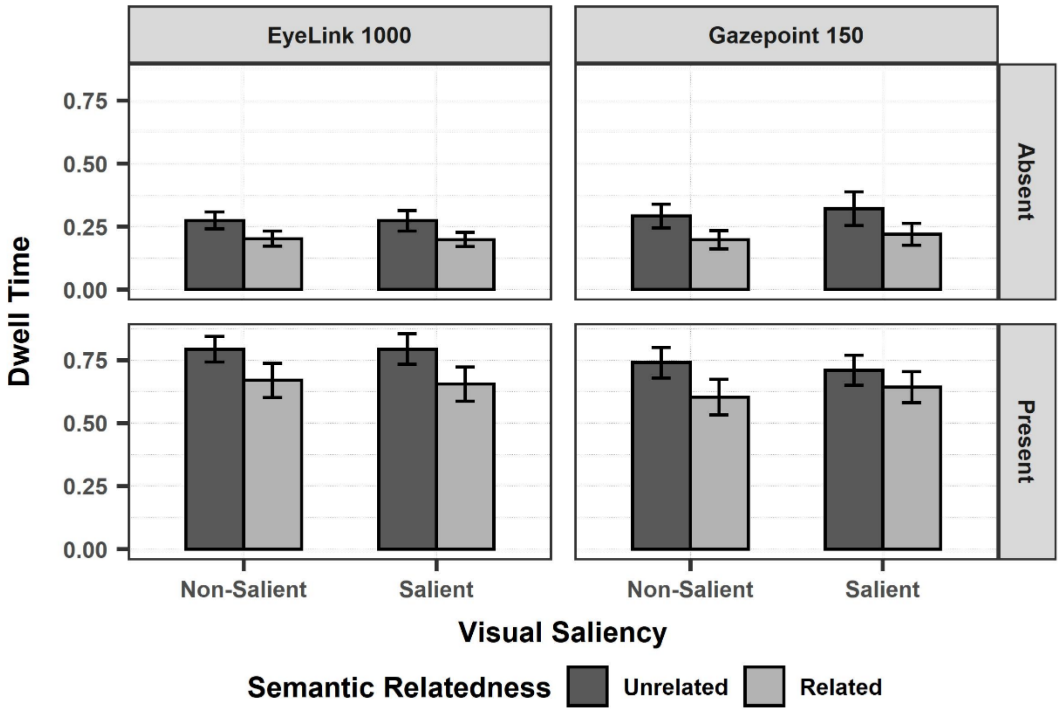


Figure 29. Mean dwell time (proportions) on the critical object for the EyeLink 1000 (left panel) and Gazepoint 150 group (right panel) on target-present and -absent trials, arranged over the rows of the panels, with the two levels of visual saliency (non-salient, salient) on the x-axis, in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

thus not retained during model selection (EyeLink 1000: *M* = .50, *SD* = .30; Gazepoint 150: *M* = .48, *SD* = .28; χ^2 = .41, *p* = .52).

The pilot study found evidence of semantic relatedness effects on measures of extra-foveal attentional capture, i.e., search latency, and foveal processing, i.e., dwell time, both when eye movements were monitored with the Gazepoint GP3 HD 150 eye-tracker and the EyeLink 1000. I did not find a significant effect of semantic relatedness on the probability of immediate fixation in both groups, presumably due to the low sample. All in all, the pilot study demonstrates that the Gazepoint GP3 HD 150 eye-tracker can detect semantic relatedness effects on eye movements in a comparable way as the EyeLink 1000.

4.2.2 Analyses

The dependent variables were response accuracy, the probability of immediate fixation, search latency (raw scores and z-scores to account for generalised slowing associated to AD; Faust et al., 1999), and dwell time on the critical object. Of the 1,600 experimental trials considered in the analysis (i.e., 40 trials x 40 participants), I discarded 4 trials because of machine error (no eye movement was recorded) and 57 trials of the target-present trials because the response in the number array did not match the search response. On the remaining trials (1,539), I analysed the response accuracy. The eye-movement measures were computed only on accurate trials in which the critical object was fixated at least once (1,178 trials). The fixed effects considered, and centred to reduce co-linearity, were: Semantic Relatedness (Unrelated = -.5, Related = .5), Visual Saliency (Non-salient = -.5, Salient = .5), Target (Absent = -.5, Present = .5), Group (Control = -.5, AD = .5), and Visual Similarity (Dissimilar = -.5, Similar = .5), whereas the random variables included, both as intercepts and slopes, were Participant (40) and Item (160).

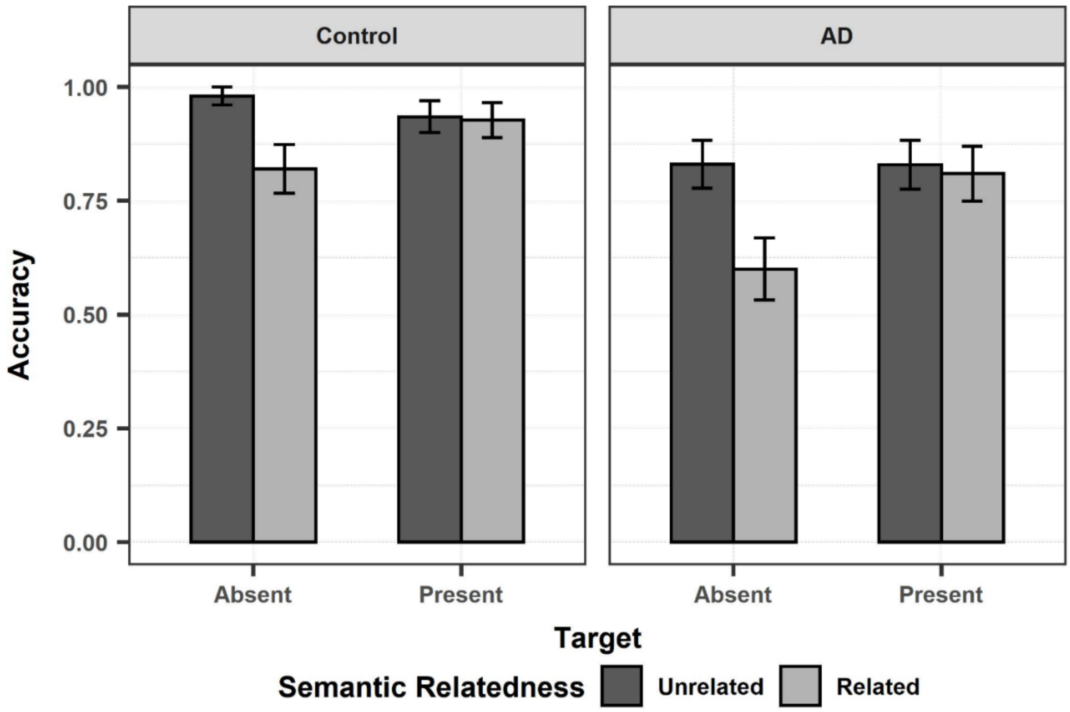


Figure 30. Mean response accuracy (proportions) for the control (left panel) and AD group (right panel), on target-present and -absent trials (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

4.2.3 Results

Before presenting the results of the analyses, it is worth highlighting that low-level visual saliency was never included, as a significant main effect, in any best-fitting model on any of the measures analysed in this experiment.

4.2.3.1 Accuracy

On response accuracy (see Figure 30), I found a significant main effect of group, whereby AD patients performed less accurately than healthy controls. There was also a significant main effect of semantic relatedness, and a significant interaction between semantic relatedness and target: accuracy was higher when the critical object was semantically unrelated than

Table 21

Generalized Linear Mixed-effects Model Output for Response Accuracy

Dependent Variable	Predictor	β	SE	z-value	Pr (> | z |)
Accuracy	Intercept	2.19	0.15	14.57	**< 0.001**
	Semantic Relatedness	- 0.91	0.20	- 4.42	**< 0.001**
	Group	- 1.32	0.23	- 5.70	**< 0.001**
	Target	0.25	0.24	1.05	0.30
	Visual Similarity	- 0.36	0.20	- 1.80	0.07
	Semantic Relatedness:Target	1.58	0.34	4.67	**< 0.001**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Semantic Relatedness (unrelated = -.5, related = .5), Group (control = -.5, AD = .5), Target (absent = -.5, present = .5) and Visual similarity (dissimilar = -.5, similar = .5).

related to the distractors, with this difference being greater in target-absent than in target-present trials (Refer to Table 21 for the model output).

4.2.3.2 Probability of immediate fixation, search latency, and dwell time

On the probability of immediate fixation, the only predictor retained during model selection was group whose main effect did not reach statistical significance (control: M = .17, SD = .38; AD: M = .14, SD = .35; β = - .29, SE = .17, z = - 1.70, p= .09), and hence was not further discussed.

On standardised search latency (Figure 31), I found a significant main effect of target. The critical object was fixated earlier on target-present than target-absent trials. Moreover, there was a significant main effect of semantic relatedness, whereby participants looked at the critical object earlier when it was semantically unrelated than related to the distractors. Neither the main effect of group, nor its interaction with the other variables included in the model were significant (See Table 22 for the model output). In the analysis of raw scores (Figure 31), I found significant main effects of target and semantic

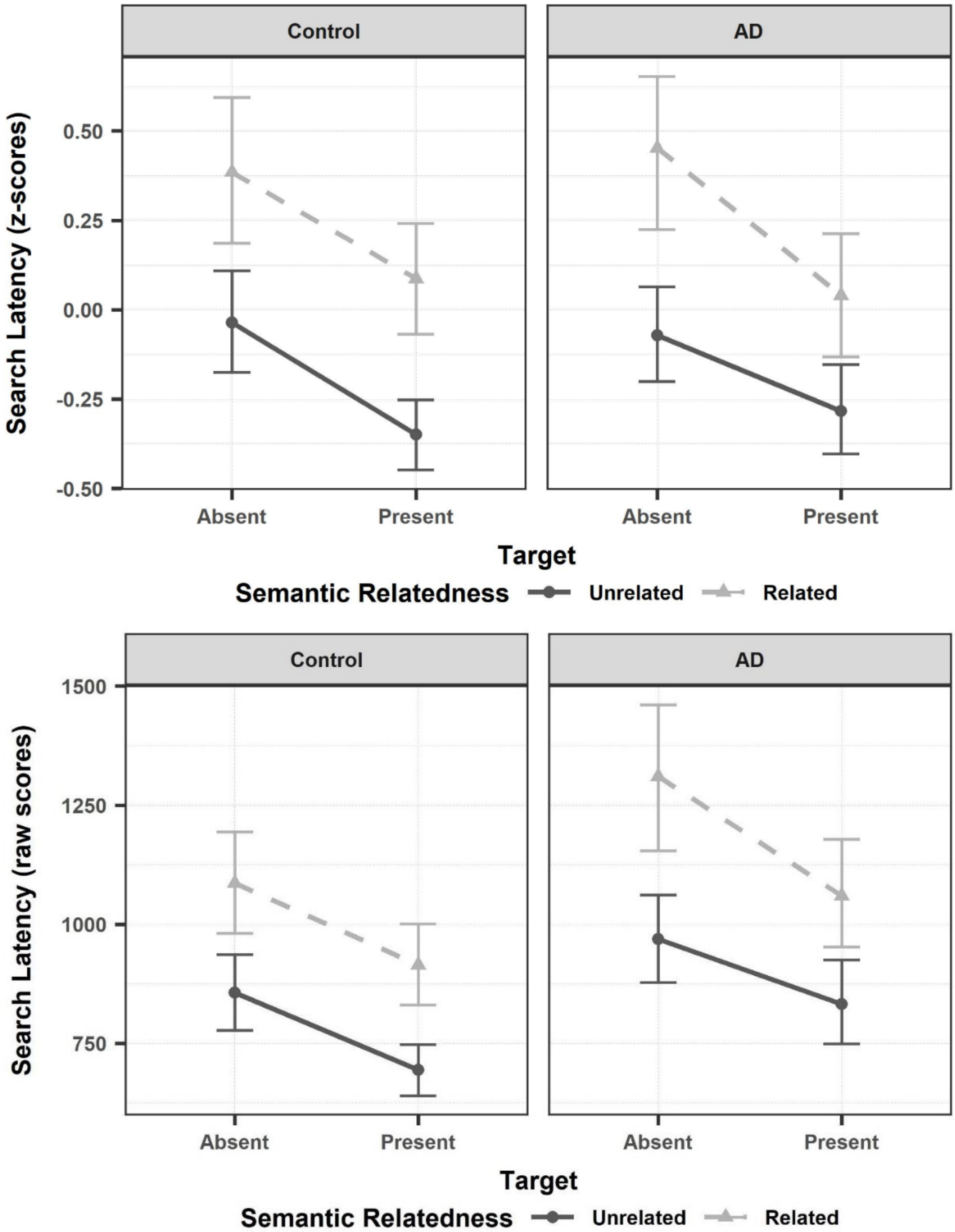


Figure 31. Mean search latency (z-scores, top; raw scores, ms, bottom) on the critical object for the control (left panel) and AD group (right panel), on target-present and -absent trials (on the x-axis), with the semantic relatedness of the critical object marked using line types and colour (unrelated: dark grey, solid line; related: light grey, dashed line). Error bars represent 95% confidence intervals around the mean.

Table 22

Linear Mixed-effects Model Output for the Search Latency on the critical object

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
Search Latency (z-scores)	Intercept	0.02	0.04	0.41	0.68
	Group	0.04	0.05	0.73	0.46
	Target	- 0.31	0.05	- 6.06	**< 0.001**
	Semantic Relatedness	0.43	0.09	4.91	**< 0.001**
	Visual Similarity	0.15	0.08	1.80	0.07
	Group:Target	- 0.01	0.10	- 0.14	0.89
	Group:Semantic Relatedness	0.02	0.13	0.20	0.84
	Group:Visual Similarity	0.09	0.10	0.91	0.37
Search Latency (raw scores)	Intercept	955.30	28.24	33.83	**<0.001**
	Target	- 183.98	31.24	- 5.89	**<0.001**
	Semantic Relatedness	260.63	54.44	4.79	**<0.001**
	Group	171.52	41.73	4.11	**<0.001**
	Visual Similarity	90.43	49.63	1.82	0.07

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Group (control = -.5, AD = .5), Target (absent = -.5, present = .5), Semantic Relatedness (unrelated = -.5, related = .5), and Visual Similarity (dissimilar = -.5, similar = .5).

relatedness, thus replicating the findings on z-scores. Moreover, I found a significant main effect of group, with the critical object looked at earlier by the control group than the AD group (Table 22).

On dwell time (Figure 32), I found significant main effects of target, with longer dwell times on target-present than -absent trials, and semantic relatedness, whereby dwell times were longer when the critical object was semantically unrelated than related to the distractors. (See Table 23 for the model output).

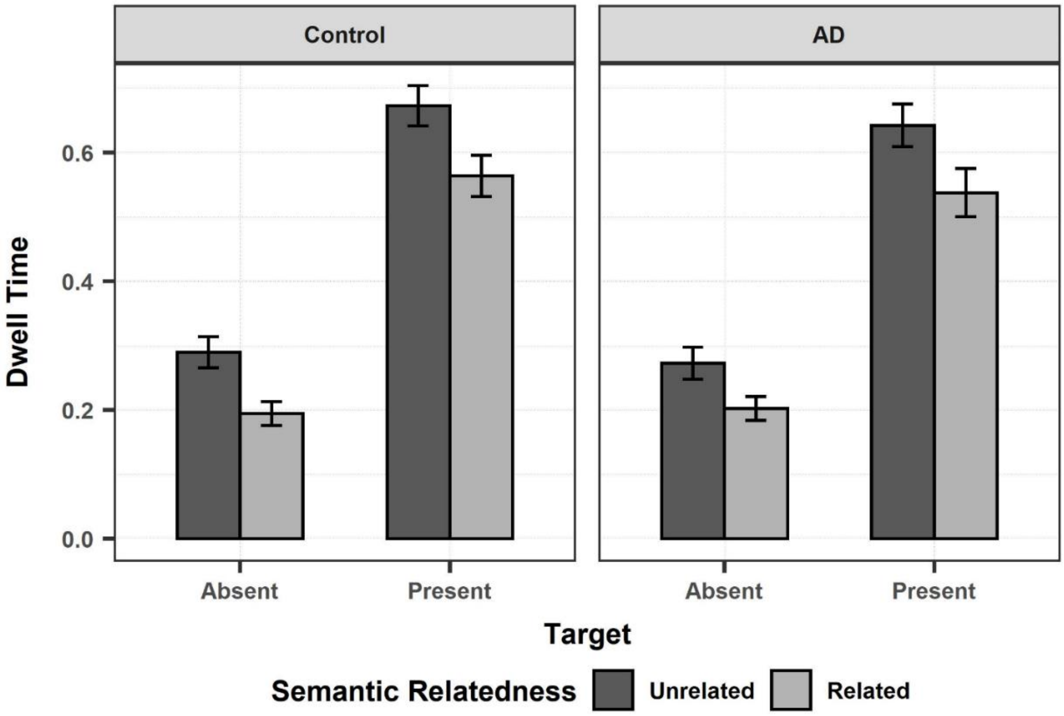


Figure 32. Mean dwell time (proportions) on the critical object for the control (left panel) and AD group (right panel), on target-present and -absent trials (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 23

Linear Mixed-effects Model Output for the Dwell Time on the Critical Object

Dependent Variable	Predictor	β	SE	t-value	Pr (> | t |)
Dwell Time	Intercept	0.43	0.01	47.52	**< 0.001**
	Target	0.36	0.01	27.32	**< 0.001**
	Semantic Relatedness	- 0.10	0.01	- 7.79	**< 0.001**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Target (absent = -.5, present = .5), and Semantic Relatedness (unrelated = -.5, related = .5).

4.2.4 Discussion

Experiment 4 investigated whether the processing of object semantic information is preserved in AD patients by looking at their eye movements during a visual search task. I employed the same experimental paradigm used for the experiments in Chapter 3, with participants presented with the name of the target object to search in arrays comprising a critical object and semantically homogeneous distractors. In target-present trials, the critical object corresponded to the search target, whereas in target-absent trials, it was a distractor semantically related to the target. Moreover, the critical object was either semantically related or unrelated to the distractors, and either salient or non-salient. In the semantic unrelated condition, the critical object was the only object sharing semantic features with the target, and it was thus expected to be prioritized by overt attention if its semantic features were processed in extra-foveal vision.

Results revealed a significant main effect of group on search accuracy, with AD patients performing worse than age-matched controls, which is in line with previous evidence that AD impairs search (Porter, Leonards, et al., 2010; Rösler et al., 2000; Tales et al., 2002). However, regardless of the group, all participants detected more accurately the critical object when it was semantically unrelated than related to the distractors. This result indicates that the semantic information of the critical object was processed enough to lead to a significant difference in its identification, and crucially, this effect was observed also in the AD group.

On eye-movement measures, I also found clear evidence of preserved semantic processing in AD patients. The analysis of standardised search latency showed that AD patients and healthy controls looked at the critical object earlier when it was semantically unrelated compared to when it was related to the distractors. This result indicates that extra-foveal processing of object semantics occurred in AD patients and, as for healthy older adults, it contributed to guiding overt visual attention.

Semantic relatedness did not affect initial eye movements, both in AD patients and in the healthy controls (replicating the findings from Experiment 3), as evidenced by the analysis of the probability of immediate fixation. This suggests that, regardless of the pathology, older adults require more fixations to orient their gaze in the visual scene, which is in line with the general slowing associated with cognitive ageing (Salthouse, 1996, 2012).

Object-to-object semantic relationships also affected eye-movement measures of fixation processing, i.e., dwell time, with the critical object looked at for longer when it was semantically unrelated than related to the distractors, similarly for the control and the AD group.

Evidence of extra-foveal processing of object semantics and its impact on target detection accuracy suggest that the semantic deficits found in previous studies on AD patients may be associated to more specific factors other than a complete loss of semantic knowledge. My explanation of preserved semantic processing of AD patients hinges around the role of the task, and especially whether it required explicit or implicit access to semantic knowledge, as well as to the nature of stimuli used, i.e., verbal vs. non-verbal. Studies reporting a semantic impairment in AD have typically used semantic memory tasks such as category fluency, object naming and word-to-picture matching tasks (Adlam et al., 2006; Holmes et al., 2006; Salmon et al., 1999), which require participants to intentionally access their semantic knowledge and retrieve relevant information. In contrast, in my experiment, I used a visual search task, which effectively entails a cueing component, i.e. the target of the search is prompted to the participant, and hence it does not require an explicit retrieval of semantic information. Moreover, I looked at eye-movement responses, which can index implicit and automatic mechanisms of semantic processing, especially in clinical populations (Hannula et al., 2010). Thus, as the task activated a specific target template through cueing and object semantics were processed in extra-foveal vision, AD patients were able to guide their eye-movement earlier to the critical object when it was semantically unrelated than when it was semantically related to the other distractor objects. The other factor that may have contributed to the preserved semantic processing in AD patients is that the stimuli used consisted of non-verbal material (i.e., pictures of objects). Such type of material is known to have a cognitive advantage over verbal material, which instead demands more complex strategies of lexical matching and retrieval (Ally, Gold, et al., 2009; Bartolo et al., 2016; Rich et al., 2002).

Finally, in order to make sure that evidence of preserved visual guidance by object semantics was not related to individual differences in the verbal semantic abilities of the AD patients, I correlated the AD patients' individual scores on the Rey test with their average search latency to look at the semantically unrelated critical objects. This additional analysis shows no significant correlation between the two [$r(18) = -0.13$, $p = 0.6$]. This finding seems to argue against the notion of a unitary semantic memory system (Bright, Moss, & Tyler, 2004; Lambon Ralph, Patterson, & Hodges, 1997) and suggests that the semantic system may instead be divided into modality-specific subsystems, which interact with one another but separately deal with pictures and words (Paivio, 2014; Saffran, Branch Coslett, Martin, & Boronat, 2003).

In sum, Experiment 4 suggests that AD patients do retain semantic knowledge and can access it when the task involves implicit memory and automatic processes and it utilises non-verbal stimuli, probably indicating that they present deficits when this knowledge has to be intentionally and explicitly retrieved.

Altogether, the experiments presented in Chapters 3 and 4 highlight the strong role played by object semantic information in guiding overt attention, above and beyond other factors, i.e., low-level visual saliency and visual similarity. Visual saliency did not influence any of the eye-movement measures analysed in my experiments. This is not surprising, as visual saliency is thought to play a strong role in attentional allocation in non-cued visual tasks, e.g., memorization, rather than in cued search tasks. Given this, in the next chapter, I used the same stimuli in a memorization task to examine the interplay of visual saliency and semantic information in the guidance of overt attention, and memory performances, of younger (Experiment 5) and older adults (Experiment 6).

5 Object semantics affect memory performances of younger and older adults by guiding overt attention

5.1 Introduction

In contrast to a visual search task, where observers are asked to inspect a visual context in search of a specific object, i.e., target object, in a memorization task, no target object is specified. The relevance of an object in the visual context is thus determined only by the observer, who can rely on either bottom-up, top-down information, or both to guide attention (Coco et al., 2014; Foulsham & Underwood, 2007). Memorization tasks put bottom-up and top-down information directly in competition, and are thus ideal to understand their relative contribution to guiding visual attention. Several studies show that low-level visual saliency and high-level semantic information of objects in naturalistic scenes interact in affecting eye-movement behaviour when the task does not cue a specific target object to look at. However, previous research provides inconclusive evidence about how this interplay takes place, with some studies finding a predominant influence of visual saliency (Coco et al., 2014; Underwood & Foulsham, 2006), and others reporting a prioritization for semantic information (Nyström & Holmqvist, 2008; Spotorno & Tatler, 2017; Underwood et al., 2008). It is also unclear whether differences in the allocation of overt attention towards objects as a function of their saliency and semantic features can explain differences in their memorization. Despite the extensive evidence of a strong link between overt attention and memory (Botta et al., 2010; Clarke et al., 2013; Hollingworth & Henderson, 2002; B. K. Schmidt et al., 2002), the few studies examining the effects of saliency and semantic information on both eye-movement and memory responses show that the features of objects can determine whether or not they will be remembered, independently of differential patterns of attentional orientation and selection (Fine & Minnery, 2009; Silva et al., 2006; Spotorno et al., 2013). Furthermore, although previous studies showed that older adults do not rely on object semantics to guide attention during memorization as younger adults do (Suzin et al., 2019), and that the influence of visual saliency on the capture of overt attention might increase with old age (Tsvetanov et al., 2013), little is known about the extent to which the joint contribution of saliency and semantic information to attentional control and memory changes with ageing.

Chapter 5 addressed these gaps in the literature with two eye-tracking experiments which used the same stimuli as those of the previous chapters, i.e., object arrays containing a critical object which was either salient or non-salient, and semantically related or unrelated to semantically homogenous distractor objects. Participants were asked to freely inspect the object arrays and try to memorize as many objects as possible, in preparation for immediate verbal recall. Data were investigated in two different sets of analysis. The first set focused on eye-movement measures on the critical object, and examined the influence of visual saliency and semantic information on the allocation of visual attention. The second set focused on memory responses on the critical object, and examined the influence that saliency and semantic information had on the probability of recalling it and whether such influence could be explained by eye-movement behaviour at encoding.

In Experiment 5, young adults were asked to inspect and memorize arrays of different sizes (3, 5, 7), whereas in Experiment 6, younger and healthy older adults performed the same memorization task on five-object arrays only. It is worth mentioning that, although the two experiments in this chapter are presented sequentially, Experiment 6 does not temporally follow Experiment 5. Due to the restricted time window available to recruit participants, data collection and analysis for these two experiments were conducted simultaneously.

5.2 Experiment 5

Experiment 5 aimed to provide fresh evidence on the interplay between the low-level saliency and high-level semantic information of objects on the distribution of overt attention during a memorization task. Also, it examined their effects on memory and whether these effects follow from differences in the eye-movement patterns at the time of inspection; for example, a salient object might be recalled more often than a non-salient one because it receives more attentional resources, e.g., it is more likely to be fixated.

In line with previous research on the relationship between saliency, semantic relatedness, and memory, I expected the critical object to be recalled more often when salient and semantically related to the distractors (Guerin & Miller, 2008; Pedale & Santangelo, 2015; Poirier et al., 2015; Saint-Aubin et al., 2005). Suzin et al. (2019) suggested that the effect of semantic relatedness of objects on memory recall is, at least in part, the result of using a semantic scanning pattern. That is, observers move their gaze towards objects that are semantically related to the currently fixated one, which would facilitate their encoding. Thus, if overt attention during memorization is guided by the extra-foveal processing of the semantic features shared by visual stimuli, I expected participants to be more likely to fixate the critical object, and/or to look at it earlier and for longer, when semantically related than unrelated to the distractors. I also expected semantic relatedness to interact with visual saliency in guiding the allocation of overt attention, in line with previous research on naturalistic scenes. This interaction might favour saliency (Coco et al., 2014; Underwood & Foulsham, 2006), whereby when the critical object was salient, the effect of semantic relatedness would not emerge, or be strongly reduced. Otherwise, it might favour semantic information (Nyström & Holmqvist, 2008; Spotorno & Tatler, 2017; Underwood et al., 2008), whereby a semantically related critical object would be prioritized by overt attention even when of lower saliency than a semantically unrelated one.

In Experiment 5, participants inspected arrays of different sizes. This allowed me to examine whether and how the contribution of bottom-up and top-down information to attention and memory changes with increasing task difficulty, i.e., more objects to be inspected and recalled. The effects of visual saliency and semantic relatedness on eye movements and verbal recall could be less evident with three-object arrays (the task might be too easy), and emerge more strongly with five- and seven-object arrays, where more stimuli compete for attentional and memory resources (see Fine & Minnery, 2009, for related findings).

5.2.1 Methods

5.2.1.1 Participants

A total of 72 participants (49 women), students at the University of Edinburgh, and aged between 18 and 30 years (*M* = 20.74, *SD* = 3.03), participated in the study for either course credits or a £3.50 honorarium. All participants were native English speakers and had a normal or corrected-to-normal vision.

5.2.1.2 Design

A 2x2x3 mixed factorial design was used with two within-participants variables, Semantic Relatedness (unrelated, related) and Visual Saliency (non-salient, salient) and a between-participants variable, Set Size (3, 5, 7), and participants equally divided among the different set sizes (i.e., 24 participants each).

5.2.1.3 Stimuli

The visual contexts for Experiment 5 consisted in the same 384 experimental arrays of objects used for Experiments 1 and 2 in Chapter 3, presented at the same resolution of 1024 x 768 pixels, at the same viewing distance of 82 cm (28.07° and 21.40° of visual angle on the horizontal and on the vertical axis, respectively).

5.2.1.4 Procedure

At the beginning of each experimental session, each participant received written and verbal instructions about the task to be performed. A 9-point calibration and validation procedure were run to setup the eye-tracking accuracy. Each trial began with a drift correction after which a fixation cross appeared at the centre of the screen, followed by an object array (encoding phase). The presentation of the object array was triggered by the experimenter pressing the “F” key, on his keyboard, as soon as participants looked at the central fixation cross. Participants were asked to freely inspect the arrays and memorize as many objects as possible for later verbal recall. The duration of the encoding phase varied depending on the number of objects on the array: 1400, 2200, and 3200 ms for set sizes 3, 5, and 7, respectively. These represent the values corresponding to the 95th percentile within the distribution of data taken from Experiments 1 and 2 on the time needed by young adults to fixate either 3, 5, or 7 objects during a visual search task. This choice is motivated by previous studies suggesting that the effects of object semantics on overt attention might not emerge in memorization tasks where the time available to inspect the visual context is too long, i.e., participants might not be motivated to use extra-foveal object semantic information to guide attention because of the unspeeded nature of the task (Henderson et al., 1999; Võ & Henderson, 2009). Accordingly, asking participants to inspect and memorize the object arrays with limited time should increase the contribution of top-down information to the attraction of eye movements. Then, after a 1,000 ms retention interval during which the central fixation cross was presented again (maintenance phase), an audible beep was played prompting participants to verbally recall as many objects as they could while looking at a blank screen (recollection phase). Participants had been instructed to identify, not to describe, the objects, e.g., "red chair" is not preferred over "chair"; and to be as specific as they could in their identification, e.g., "pigeon" is preferred over "bird", "hammer" is preferred over "tool". The recollection phase lasted for 15,000 ms (time-out) or until participants said "stop" aloud, i.e., they were confident to not be able to remember any more objects. On hearing "stop", the experimenter pressed the "space" key on the experimenter keyboard to trigger the next display. Then, the text label "Stop Recalling" appeared at the centre of the screen for 1,000 ms followed by a 500 ms blank screen (inter-trial interval) (See Figure 33 for an example of a trial run). Each participant completed 4 practice trials and 32 randomized unique experimental trials, which were counterbalanced across the conditions of visual saliency and semantic relatedness using a Latin square rotation, in one specific set size (i.e., either 3, 5, or 7). The experimental session lasted approximately 15 minutes.

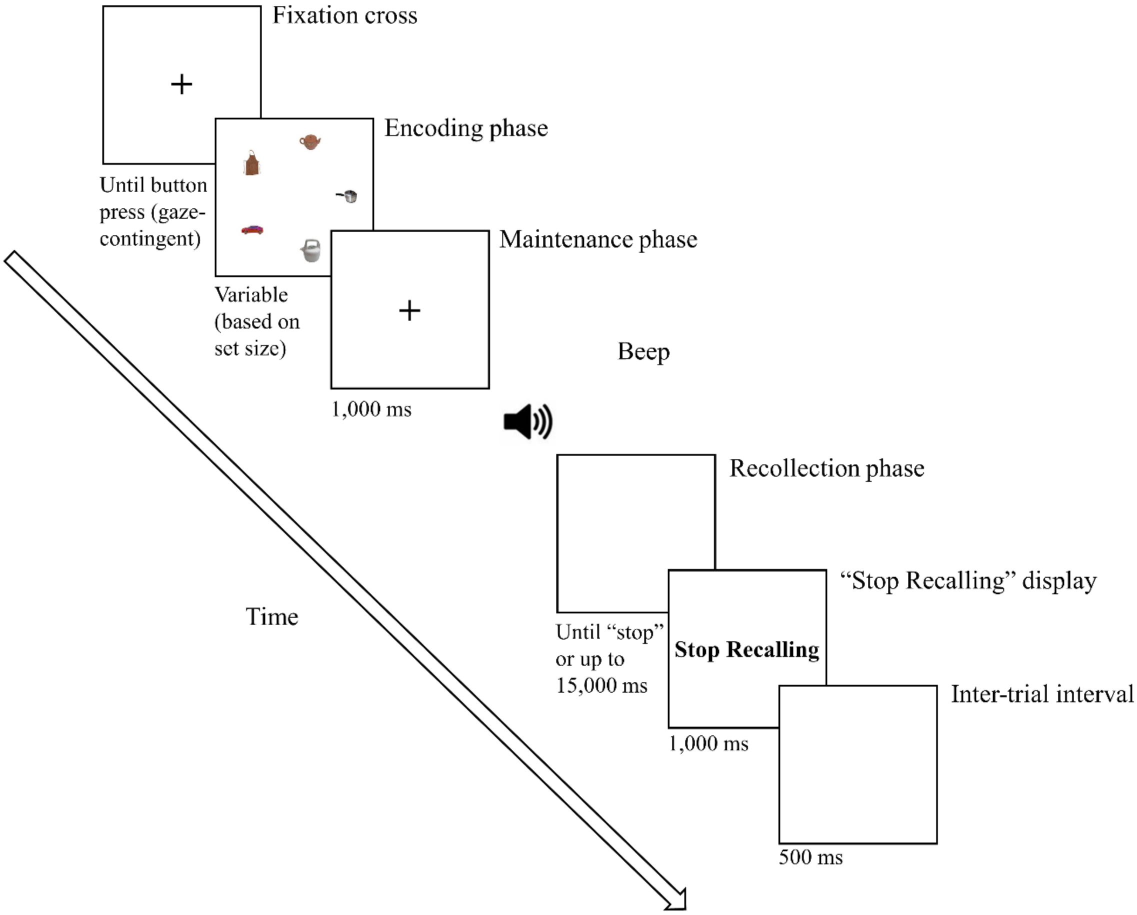


Figure 33. Example of a trial run. The central fixation cross was displayed until participants looked at it for the first time. Once it was fixated, the experimenter pressed the “F” key on his keyboard to trigger the presentation of the object array (encoding phase). The duration of the encoding phase was based on the number of objects on the array: 3 (1,400 ms), 5 (2,200 ms), or 7 (3,200 ms) objects. Following a 1,000 ms retention interval (maintenance phase), an audible beep was played, and a blank screen displayed (recollection phase). The beep cued participants to start recalling the objects. The recollection phase lasted until participants could not remember any more objects, i.e., they said “stop” aloud and the experimenter pressed the “space” key on his keyboard to trigger the onset of the next display, or up to 15,000 ms.

5.2.2 Analyses

The dependent variables measured were recollection probability, fixation probability, time to first fixation, and total fixation duration on the critical object (See Chapter 2 for a detailed description of the dependent variables). Of the 2,304 experimental trials (i.e., 32 trials x 72 participants), 114 trials were discarded because of machine error (no eye movement was recorded). On the remaining trials (2,190), I analysed the recollection probability and the fixation probability, whereas the time to first fixation, and the total fixation duration were computed only on trials in which the critical object was fixated at least once (1,943).

Data were analysed by using used linear and generalized linear mixed-effects models (G/LMM). In particular, the fixed effects considered, and centred to reduce co-linearity, were: Semantic Relatedness (Unrelated = -.5, Related = .5), Visual Saliency (Non-salient = -.5, Salient = .5), Set Size (3, 5, 7), where I used the set size of 3 as the reference level (3 vs. 5: 3 = -.5, 5 = .5; and 3 vs. 7: 3 = -.5, 7 = .5), and Visual Similarity, (Dissimilar = -.5, Similar = .5). The random variables included in the models, both as intercepts and slopes, were Participant (72) and Item (384).

5.2.3 Results

5.2.3.1 Fixation probability, time to first fixation, and total fixation duration

On the fixation probability (Figure 34; also see Table 24 for the descriptive statistics, i.e., mean and standard deviation), there was a significant main effect of set size. The probability of looking at the critical object was higher for set size 3 than 5, and 7. I also found a significant main effect of semantic relatedness, whereby the critical object was more likely to be fixated when it was semantically related than unrelated to the distractors (See Table 25 for the model output).

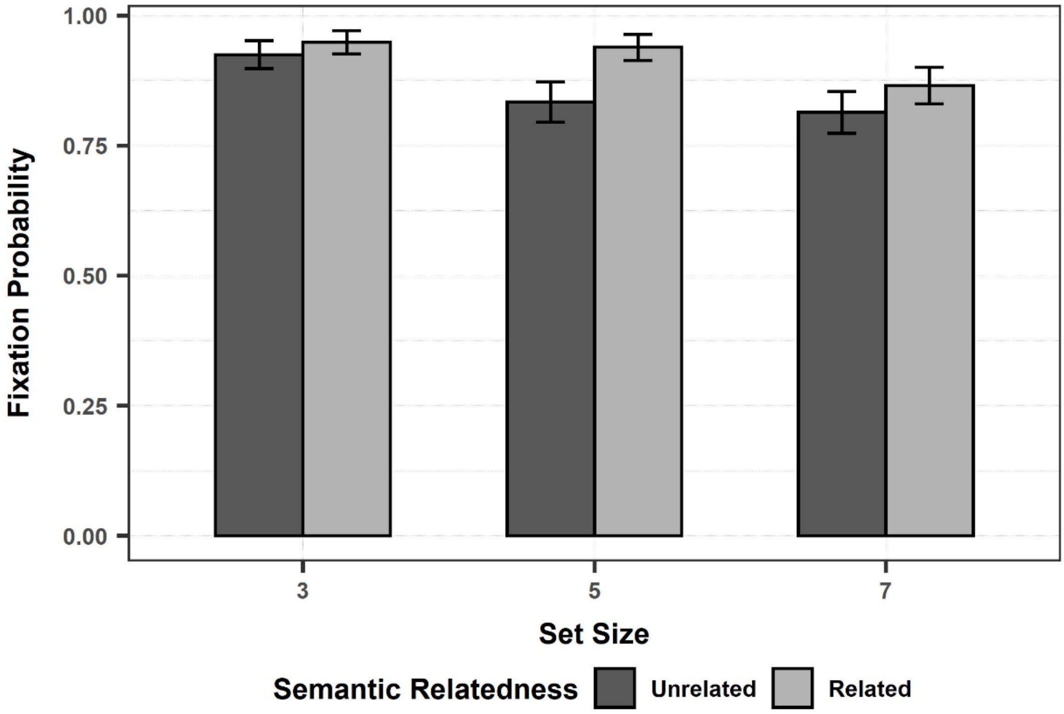


Figure 34. Mean fixation probability (proportions) of the critical object for set sizes 3, 5, and 7 (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 24

Mean and Standard Deviation (in Parenthesis) of the Fixation Probability of the Critical Object (Proportions) by Experimental Condition

3				5				7			
Unrelated		Related		Unrelated		Related		Unrelated		Related	
Non-salient	Salient	Non-salient	Salient	Non-salient	Salient	Non-salient	Salient	Non-salient	Salient	Non-salient	Salient
.93 (.26)	.92 (.27)	.96 (.20)	.94 (.24)	.83 (.38)	.84 (.37)	.94 (.23)	.93 (.25)	.80 (.40)	.83 (.38)	.85 (.36)	.88 (.33)

Table 25

Generalized Linear Mixed-effects Model Output for the Fixation Probability of the Critical Object

Dependent Variable	Predictor	β	SE	z-value	Pr (> | z |)
Fixation Probability	Intercept	3.25	0.27	12.11	**< 0.001**
	Semantic Relatedness	0.72	0.18	4.04	**< 0.001**
	Set size (3 vs. 5)	- 0.76	0.33	- 2.31	**0.02**
	Set size (3 vs. 7)	- 1.16	0.32	- 3.60	**< 0.001**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Semantic Relatedness (unrelated = -.5, related = .5) and Set Size (3, 5, 7). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

A follow-up analysis conducted on the subset of data for each set size, separately, showed that the effect of semantic relatedness was statistically significant only for set size 5 (β = 1.16, *SE* = .30, z = 3.88, p < .001), and 7 (β = .48, *SE* = .24, z = 2.00, p< .05), but not for set size 3 (χ^2 = 1.07, p = .30; semantic relatedness did not significantly improve the model fit during model selection).

On the time to first fixation to the critical object, results showed a significant effect of set size, whereby the critical object was looked at earlier in set size 3 (*M* = 654.29, *SD* = 395.84) than 5 (*M* = 1001.43, *SD* = 639.29; β = 347.00, *SE* = 60.88, t = 5.70, p < .001) and 7 (*M* = 1373.91, *SD* = 933.87; β = 719.33, *SE* = 61.05, t = 11.78, p < .001). Neither visual saliency (non-salient: *M* = 1029.90, *SD* = 754.46; salient: *M* = 962.66, *SD* = 731.02; χ^2 = 2.55, p = .11), nor semantic relatedness (unrelated: *M* = 1019.01, *SD* = 757.91; related: *M* = 975.33, *SD* = 729.43; χ^2 = 1.29, p = .26) significantly improved the model fit during model selection.

On total fixation duration, I found a significant main effect of set size, with shorter fixation durations for the critical object in set size 3 (*M* = 332.38,

SD = 143.98) than 7 (M = 402.41, SD = 193.55; β = 72.54, SE = 15.14, t = 4.79, p < .001), but not 5 (M = 343.00, SD = 163.05; β = 12.26, SE = 15.08, t = .81, p = .42). Again, neither visual saliency (non-salient: M = 356.39, SD = 158.57; salient: M = 359.81, SD = 180.67; χ^2 = .10, p = .75), nor semantic relatedness (unrelated: M = 354.66, SD = 174.18; related: M = 361.30, SD = 165.81; χ^2 = .42, p = .52) were retained during model selection as they did not significantly improve the fit of the best-fitting model.

5.2.3.2 Recollection probability

On recollection probability (Figure 35; also see Table 26 for the descriptive statistics, i.e., mean and standard deviation), I found a significant main effect of set size, with the critical object more likely to be recalled in set size 3 than 5, and 7. Moreover, there was a significant main effect of semantic relatedness, whereby the critical object was recalled more often when it was semantically related than unrelated to the distractors (See Table 27 for the model output). When looking at Figure 35, semantic relatedness did not seem to play a significant effect in set size 3, presumably because performances were at ceiling. Thus, I conducted a follow-up analysis on the subset of data for each set size, separately. I found that the critical object was more likely to be recalled when it was semantically related than unrelated to the distractors in set size 5 (β = .48, SE = .22, z = 2.17, p < .05) and 7 (β = .55, SE = .23, z = 2.37, p < .05), but not in set size 3 (χ^2 = .00, p = .98; semantic relatedness did not significantly improve the model fit during model selection).

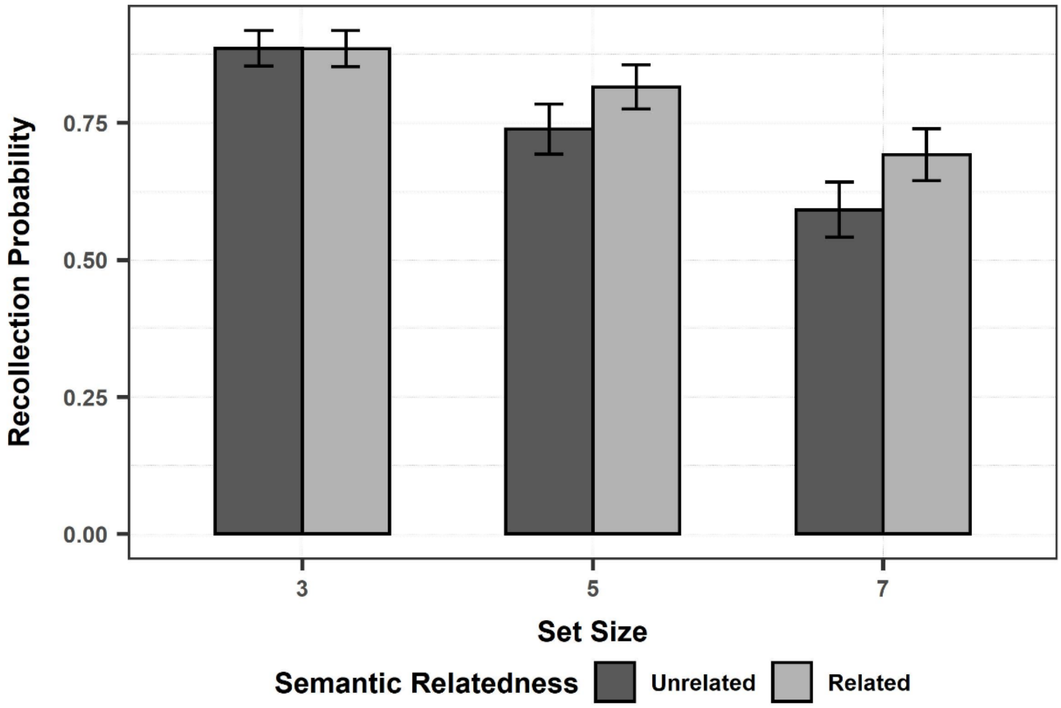


Figure 35. Mean recollection probability (proportions) of the critical object for set sizes 3, 5, and 7 (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 26

Mean and Standard Deviation (in Parenthesis) of the Recollection Probability of the Critical Object (Proportions) by Experimental Condition

3				5				7			
Unrelated		Related		Unrelated		Related		Unrelated		Related	
Non-salient	Salient	Non-salient	Salient	Non-salient	Salient	Non-salient	Salient	Non-salient	Salient	Non-salient	Salient
.90 (.29)	.87 (.34)	.90 (.30)	.87 (.33)	.71 (.45)	.77 (.42)	.81 (.39)	.82 (.39)	.56 (.50)	.62 (.49)	.64 (.48)	.75 (.44)

Table 27

Generalized Linear Mixed-effects Model Output for the Recollection Probability of the Critical Object

Dependent Variable	Predictor	β	SE	z-value	Pr (> | z |)
Recollection Probability	Intercept	2.41	0.18	13.75	**< 0.001**
	Set size (3 vs. 5)	- 0.93	0.22	- 4.27	**< 0.001**
	Set size (3 vs. 7)	- 1.70	0.21	- 7.93	**< 0.001**
	Semantic Relatedness	0.40	0.15	2.67	**0.008**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Set Size (3, 5, 7) and Semantic Relatedness (unrelated = -.5, related = .5). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

The memory advantage for semantically related critical objects might have been caused by the preferential allocation of overt attention towards them during the inspection of the object arrays. Indeed, the analysis of the fixation probability showed that the critical object was more likely to be fixated when it was semantically related than unrelated to the distractors. In the next analysis, I fitted a model which had again recollection probability as dependent variable, and semantic relatedness, visual saliency, visual similarity, and set size as fixed effects, but it also included a new binary, categorical, independent variable i.e., Fixation Probability, indicating whether the critical object was fixated, or not, during the inspection of the arrays (centred, Non-fixated = -.89, Fixated = .11). This analysis, which was conducted on all trials available (2,190), allowed me to test whether semantic relatedness still affected memory performances after controlling for the potential influence of eye movements. The results showed that it was not the case (Figure 36; see also Table 28). I found a significant effect of fixation probability, whereby fixated objects were more likely to be recalled than

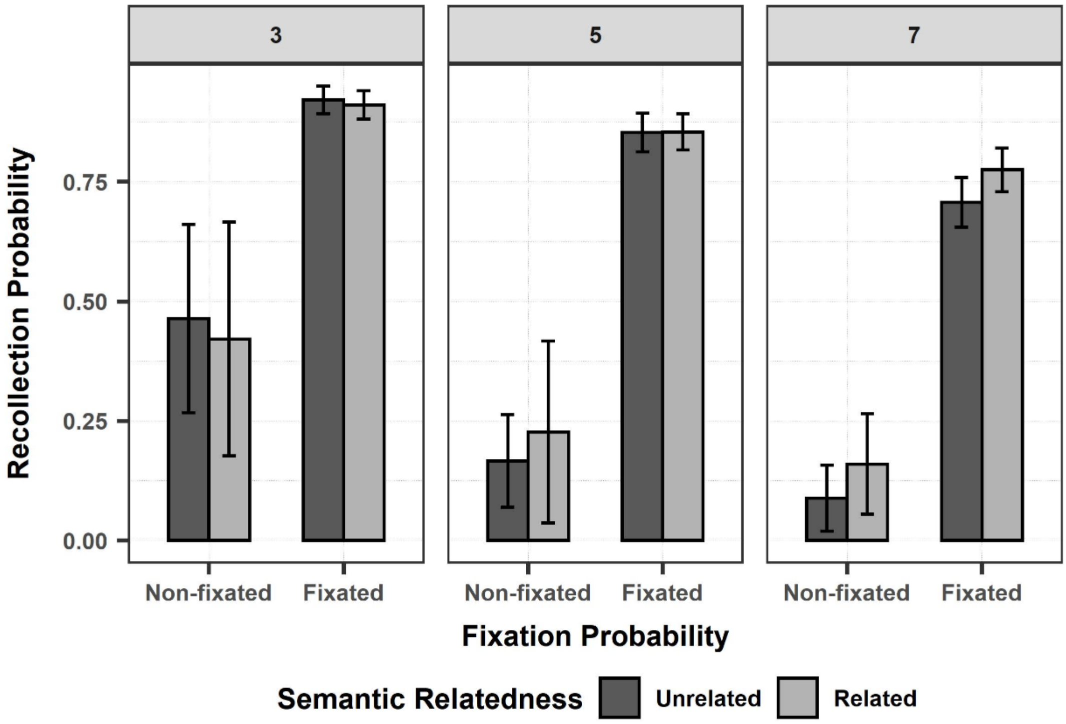


Figure 36. Mean recollection probability (proportions) of the critical object for set sizes 3 (left panel), 5 (central panel), and 7 (right panel), when non-fixated vs. fixated (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 28

Mean Proportions of Fixated and Recalled Critical Objects for Each Set Size

	3		5		7	
	Non-fixated	Fixated	Not fixated	Fixated	Not fixated	Fixated
Non-recalled	0.04	0.08	0.09	0.13	0.14	0.22
Recalled	0.03	0.86	0.02	0.76	0.02	0.62

Table 29

Generalized Linear Mixed-effects Model Output for the Recollection Probability of the Critical Object

Dependent Variable	Predictor	β	SE	z-value	Pr (> | z |)
Recollection Probability	Intercept	2.56	0.20	12.68	**< 0.001**
	Fixation Probability	3.62	0.23	15.54	**< 0.001**
	Set size (3 vs. 5)	- 0.88	0.25	- 3.55	**< 0.001**
	Set size (3 vs. 7)	- 1.65	0.25	- 6.74	**< 0.001**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Fixation Probability (non-fixated = -.89, fixated = .11) and Set Size (3, 5, 7). Two planned comparisons were set for set size: 3 vs. 5 (3 = -.5, 5 = .5) and 3 vs. 7 (3 = -.5, 7 = .5).

non-fixated ones; and a significant effect of set size, with the critical object more likely to be recalled in set size 3 than 5, and 7 (See Table 29 for the model output). Semantic relatedness did not have a significant effect on recollection probability ($\chi^2 = 1.16$, $p = .28$; semantic relatedness was not retained during model selection as it did not significantly improve the model fit).

5.2.4 Discussion

Experiment 5 showed the influence of semantic relatedness among objects on memory. The critical object was recalled more often when it was semantically related than unrelated to the distractors (in set sizes 5 and 7, only). Differences in memory performances depended on differences in the allocation of overt attention to the critical object, which was more likely to be fixated when it was semantically related than unrelated to the distractors (in set sizes 5 and 7, only). Visual saliency had no effect on memory performances and on any of the eye-movement measures analysed.

In the next section, I present Experiment 6 which used the same task to investigate how ageing affects the contribution of visual saliency and semantic relatedness information to guiding visual attention during a memorization task, and how and whether age-related differences in the allocation of overt attention could explain differences in memory performances.

5.3 Experiment 6

In Experiment 6, younger and healthy older adults performed the same memorization task as in Experiment 5. They were asked to freely inspect object arrays comprising a critical object and four distractor objects, in preparation for an immediate verbal recall task. The critical object was either salient, or non-salient, and either semantically related or unrelated to the distractors, which were always semantically related among them.

Previous research shows that older adults do not rely on the semantic relatedness among objects to guide attention during memorization as younger adults do (Suzin et al., 2019), whereas the influence of visual saliency on attentional control seems to increase with ageing (Tsvetanov et al., 2013). On this basis, I expected visual saliency to have a stronger effect on eye movements, e.g., earlier, and longer fixations for salient than non-salient objects, in older compared to younger adults. Also, if the attentional prioritisation of salient objects facilitates their probability to be encoded and stored in memory, as suggested by Pedale and Santangelo (2015), I expected salient objects to be more likely recalled than non-salient objects, with this effect being more pronounced for older adults.

5.3.1 Methods

5.3.1.1 Participants

Twenty-four younger adults (18 women), students at the University of Edinburgh and aged between 18 and 22 years (M = 19.12, SD = 1.03), as well as 24 older adults (18 women), recruited via the University of Edinburgh's volunteer panel and aged between 65 and 82 years (M = 71.71, SD = 4.67), participated in the experiment for a £3.50 honorarium. The two groups did not differ significantly in years of education (younger: M = 14.08, SD = .88; older: M = 14.67, SD = 2.79; $t(27.53)$ = .98, p = .34). All participants were native English speakers and had a normal or corrected-to-normal vision, with no history of neurological and/or psychiatric illness. All participants were screened for mild cognitive impairment using the Montreal Cognitive Assessment Test, MoCA, (Nasreddine et al., 2005), and performed above the cut-off score of 26 (scores of 25 or below indicate impairment). The MoCA scores of the younger group (M = 28.50, SD = 1.18) did not differ significantly from those of the older group (M = 28.17, SD = 1.55), $t(42.94)$ = -.83, p = .41.

5.3.1.2 Design

A 2x2x2 mixed factorial design was used with Semantic Relatedness (unrelated, related), and Visual Saliency (non-salient, salient) as within-participants variables, and Group (younger, older) as between-participants variable.

5.3.1.3 Stimuli

The visual contexts for Experiment 6 consisted in the same 160 five-object experimental arrays used for Experiment 3 in Chapter 3, presented at the same resolution of 1024 x 768 pixels, at the same viewing distance of 82 cm (28.07° and 21.40° of visual angle on the horizontal and on the vertical axis, respectively).

5.3.1.4 Procedure

The procedure was the same as for Experiment 5 with the exception that the encoding phase lasted for 2800 ms, which represents the value corresponding to the 95th percentile within the distribution of data taken from Experiment 3 on the time needed by older adults to fixate 5 objects during a visual search task. Each participant completed 4 practice trials and 40 randomized unique experimental trials, which were counterbalanced across the conditions of visual saliency and semantic relatedness using a Latin square rotation. The experimental session lasted approximately 20 minutes.

5.3.2 Analyses

The dependent variables measured were the same as those of Experiment 5. The time-dependent measures, i.e., time to first fixation and total fixation duration, were z-scored to account for the general slowing effect associated with ageing (Faust et al., 1999). Of the 1,920 experimental trials (i.e., 40 trials x 48 participants), 101 trials were discarded because of machine error (no eye movement was recorded). On the remaining trials (1,819), I analysed the recollection probability and fixation probability, whereas the time to first fixation, and the total fixation duration were computed only on trials in which the critical object was fixated at least once (1,653).

Data were analysed by using used linear and generalized linear mixed-effect models (G/LMM). In particular, the fixed effects considered, and centred to reduce co-linearity, were: Semantic Relatedness (Unrelated = -.5, Related = .5), Visual Saliency (Non-salient = -.5, Salient = .5), Group (Younger = -.5, Older = .5), and Visual Similarity, (Dissimilar = -.5, Similar = .5). The random variables included in the models, both as intercepts and slopes, were Participant (48) and Item (160).

5.3.3 Results

5.3.3.1 Fixation probability, time to first fixation, and total fixation duration

On fixation probability (Figure 37; also see Table 30 for the descriptive statistics, i.e., mean and standard deviation), there was a significant main

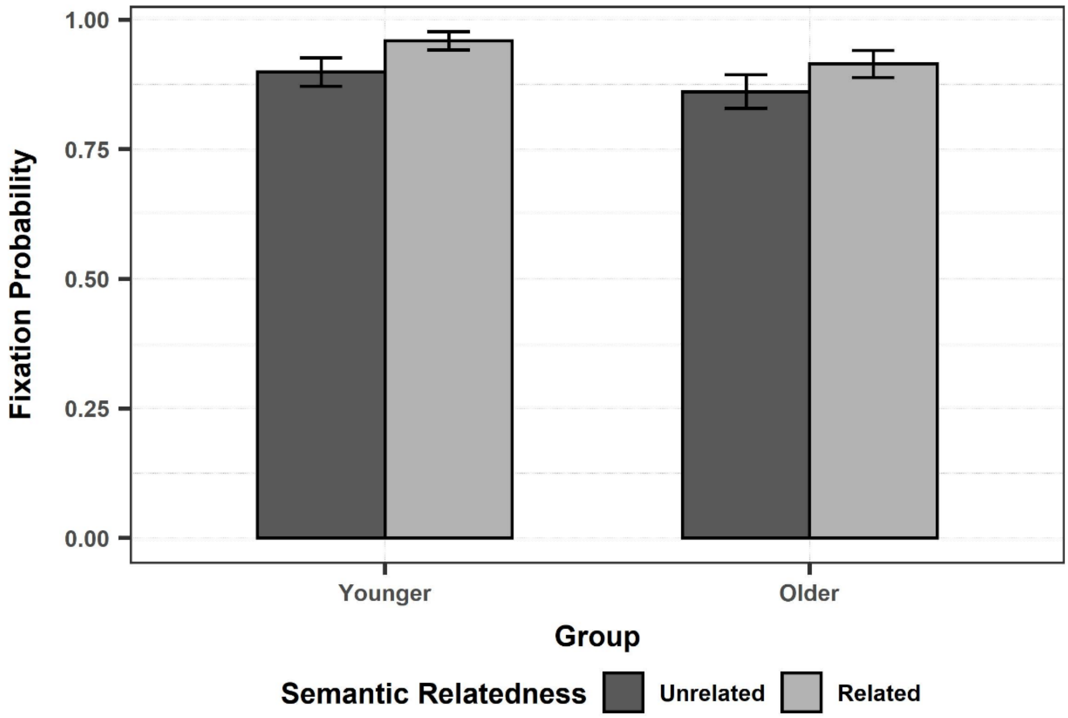


Figure 37. Mean fixation probability (proportions) of the critical object for the younger and the older group (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 30

Mean and Standard Deviation (in Parenthesis) of the Fixation Probability of the Critical Object (Proportions) by Experimental Condition

Younger				Older			
Unrelated		Related		Unrelated		Related	
Non-salient	Salient	Non-salient	Salient	Non-salient	Salient	Non-salient	Salient
.92 (.27)	.88 (.33)	.97 (.18)	.95 (.21)	.87 (.34)	.85 (.36)	.91 (.28)	.92 (.28)

Table 31

Generalized Linear Mixed-effects Model Output for the Fixation Probability of the Critical Object

Dependent Variable	Predictor	β	SE	z-value	Pr (> | z |)
Fixation Probability	Intercept	2.62	0.15	17.80	**< 0.001**
	Semantic Relatedness	0.74	0.20	3.63	**< 0.001**
	Group	- 0.53	0.22	- 2.39	**0.02**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Semantic Relatedness (unrelated = -.5, related = .5) and Group (younger = -.5, older = .5).

effect of group, whereby younger adults were more likely to fixate the critical object than older adults. I also found a significant main effect of semantic relatedness. The critical object was more likely to be fixated when it was semantically related than unrelated to the distractors (See Table 31 for the model output).

On the standardised time to first fixation, the main effect of group was not significant (younger: *M* = .00, *SD* = .10; older: *M* = .00, *SD* = .10; β = .00, *SE* = .04, *t* = .08, *p* = .94). Neither visual saliency (non-salient: *M* = .03, *SD* = .97; salient: *M* = -.03, *SD* = 1.00; χ^2 = .31, *p* = .58), nor semantic relatedness (unrelated: *M* = .08, *SD* = 1.04; related: *M* = -.07, *SD* = .92; χ^2 = 3.44, *p* = .18) significantly improved the model fit during model selection. The same pattern of results was found in the analysis of raw scores. Neither group (younger: *M* = 1227.98, *SD* = 807.07; older: *M* = 1254.64, *SD* = 759.51; χ^2 = .75, *p* = .39), nor visual saliency (non-salient: *M* = 1261.47, *SD* = 774.43; salient: *M* = 1219.59, *SD* = 794.70; χ^2 = .25, *p* = .62), nor semantic relatedness (unrelated: *M* = 1300.62, *SD* = 828.68; related: *M* = 1184.27, *SD* = 736.65; χ^2 = 3.62, *p* = .16) were included, as significant main effects, in the best-fitting model.

On the standardised total fixation duration, the main effect of group was not significant (younger: *M* = .00, *SD* = .10; older: *M* = .00, *SD* = .10; *β* = -.00, *SE* = .04, *t* = -.09, *p* = .93). Neither visual saliency (non-salient: *M* = .00, *SD* = .97; salient: *M* = .00, *SD* = 1.01; χ^2 = .01, *p* = .94), nor semantic relatedness (unrelated: *M* = -.02, *SD* = 1.02; related: *M* = .02, *SD* = .95; χ^2 = .40, *p* = .53) significantly improved the model fit during model selection. The analysis of raw scores showed a significant main effect of group (younger: *M* = 423.81, *SD* = 200.27; older: *M* = 454.33, *SD* = 188.42; *β* = 29.79, *SE* = 10.36, *t* = 2.88, *p* < .01). Neither visual saliency (non-salient: *M* = 437.48, *SD* = 187.23; salient: *M* = 439.32, *SD* = 203.17; χ^2 = .02, *p* = .87), nor semantic relatedness (unrelated: *M* = 435.55, *SD* = 202.00; related: *M* = 441.08, *SD* = 188.72; χ^2 = .32, *p* = .57) were retained in the best-fitting model as significant predictors.

5.3.3.2 Recollection probability

On recollection probability (Figure 38; also see Table 32 for the descriptive statistics, i.e., mean and standard deviation), I found a significant main effect of group, whereby younger adults were more likely to recall the critical object than older adults. Moreover, there was a significant main effect of semantic relatedness, whereby the critical object was recalled more often when it was semantically related than unrelated to the distractors (See Table 33 for the model output).

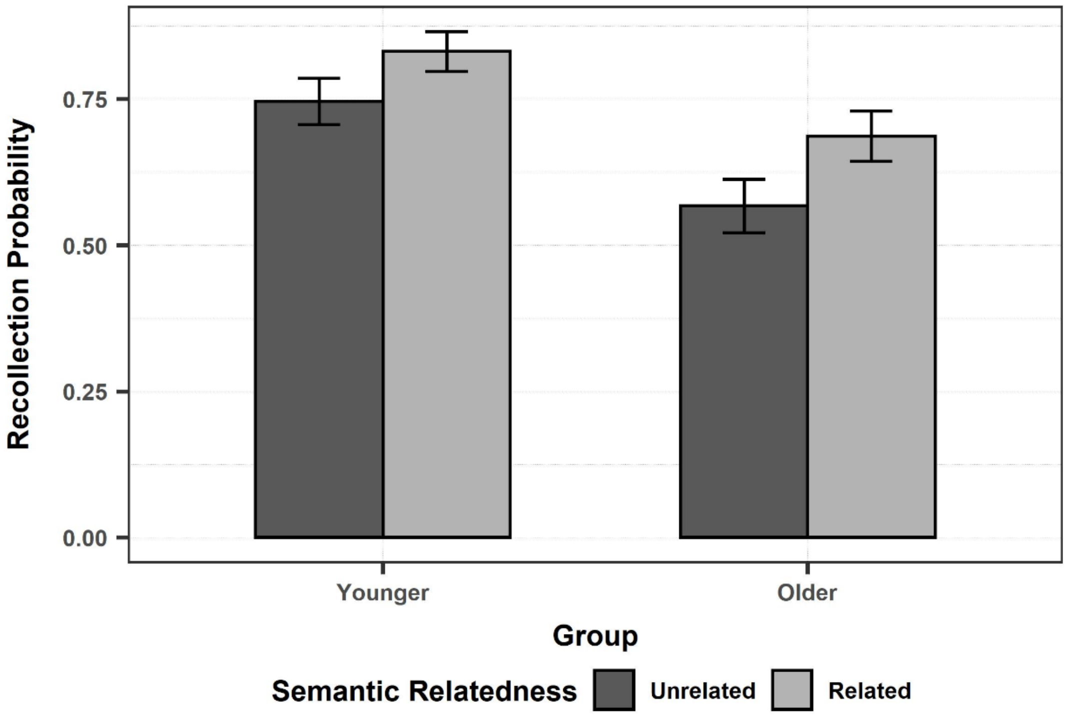


Figure 38. Mean recollection probability (proportions) of the critical object for the younger and older group (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 32

Mean and Standard Deviation (in Parenthesis) of the Recollection Probability of the Critical Object (Proportions) by Experimental Condition

Younger				Older			
Unrelated		Related		Unrelated		Related	
Non-salient	Salient	Non-salient	Salient	Non-salient	Salient	Non-salient	Salient
.74 (.44)	.76 (.43)	.84 (.37)	.83 (.38)	.55 (.50)	.59 (.49)	.67 (.47)	.71 (.46)

Table 33

Generalized Linear Mixed-effects Model Output for the Recollection Probability of the Critical Object

Dependent Variable	Predictor	β	SE	z-value	Pr (> | z |)
Recollection Probability	Intercept	1.04	0.08	12.67	**< 0.001**
	Group	- 0.89	0.11	- 7.89	**< 0.001**
	Semantic Relatedness	0.56	0.16	3.51	**< 0.001**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Group (younger = -.5, older = .5) and Semantic Relatedness (unrelated = -.5, related = .5).

The analyses of fixation probability and recollection probability showed an attentional and memory prioritisation for the critical object when semantically related than unrelated to the distractors. The effects of semantic relatedness on both attention and memory did not differ among groups. As for Experiment 5, I fitted a new model having recollection probability as dependent variable, and semantic relatedness, visual saliency, visual similarity, group, and fixation probability (centred, *Non-fixated* = -.91, *Fixated* = .09) as fixed effects. If the semantic relatedness effect on recollection probability was caused solely by the fact that the critical object was more likely to be fixated when semantically related than unrelated to the other array objects, no difference should be found on the recollection probability of semantically related and unrelated critical objects, once fixation probability is included in the model. The results showed significant main effects of fixation probability, group, and, critically, of semantic relatedness. The critical object was more likely to be recalled when fixated than non-fixated, by younger than older adults, and when it was semantically related than unrelated to the distractors (See Figure 39 and Table 34; refer to Table 35 for the model output). A follow-up analysis performed on the data of the two age groups,

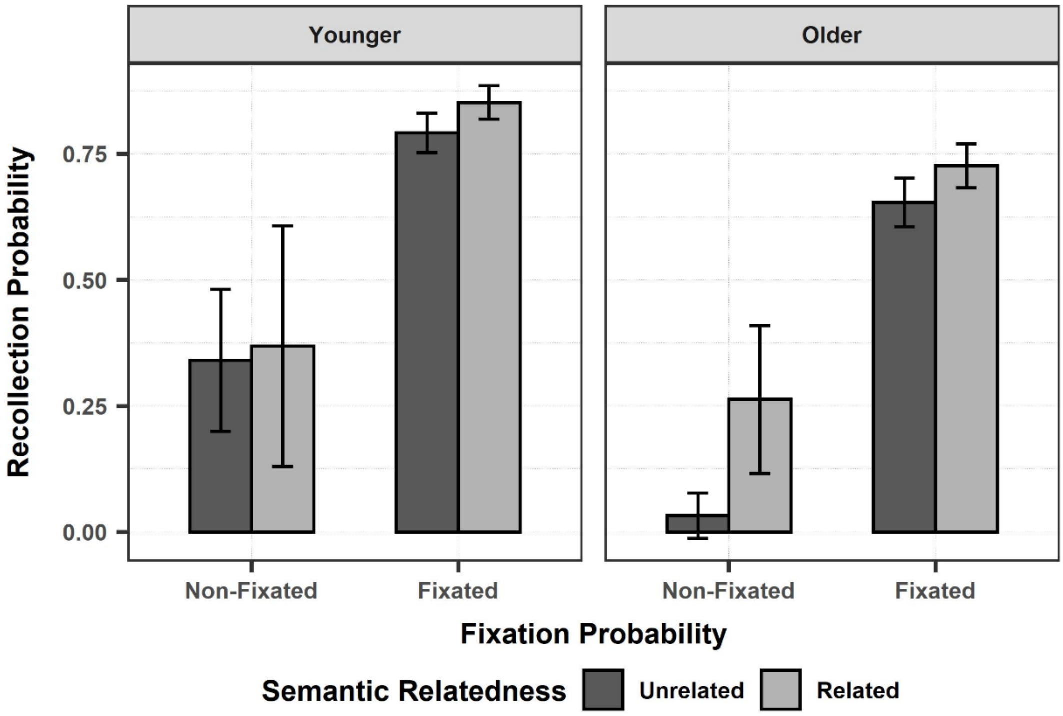


Figure 39. Mean recollection probability (proportions) of the critical object for younger (left panel), and older adults (right panel), when non-fixated vs. fixated (on the x-axis), in the semantically unrelated (dark grey) vs. related (light grey) condition. Error bars represent 95% confidence intervals around the mean.

Table 34

Mean Proportions of Fixated and Recalled Critical Objects for each Group

	Younger		Older	
	Non-fixated	Fixated	Not fixated	Fixated
Non-recalled	0.05	0.16	0.10	0.27
Recalled	0.02	0.76	0.01	0.61

Table 35

Generalized Linear Mixed-effects Model Output for the Recollection Probability of the Critical Object

Dependent Variable	Predictor	β	SE	z-value	Pr (> | z |)
Recollection Probability	Intercept	1.10	0.09	11.73	**< 0.001**
	Fixation Probability	2.79	0.24	11.77	**< 0.001**
	Group	- 0.88	0.13	- 6.94	**< 0.001**
	Semantic Relatedness	0.46	0.18	2.58	**0.01**

Note. Predictors are listed in the table in the same order as they were entered in the model. The predictors were: Fixation Probability (non-fixated = -.91, fixated = .09), Group (younger = -.5, older = .5) and Semantic Relatedness (unrelated = -.5, related = .5).

separately, showed that the effect of fixation probability was significant for both younger (non-fixated: M = .35, SD = .48; fixated: M = .82, SD = .38; β = 2.39, SE = .32, z = 7.39, p < .001), and older adults (non-fixated: M = .12, SD = .33; fixated: M = .69, SD = .46; β = 3.41, SE = .45, z = 7.55, p < .001). The effect of semantic relatedness was significant for older adults (unrelated: M = .57, SD = .50; related: M = .69, SD = .46; β = .59, SE = .22, z = 2.71, p < .01), but not for younger adults (unrelated: M = .75, SD = .44; related: M = .83, SD = .37; β = .42, SE = .21, z = 1.95, p = .06). For the older group, the significant effect of semantic relatedness was more pronounced when the critical object was non-fixated than fixated (β = - 2.00, SE = .87, z = - 2.30, p < .05; for the significant two-way interaction between semantic relatedness and fixation probability).

5.3.4 Discussion

Experiment 6 replicated the findings of semantic relatedness effect on the memory performances of younger adults found in Experiment 5, whereby the critical object was recalled more often when semantically related than unrelated to the distractors. The effect of semantic relatedness on the recollection probability of younger adults was due to a preferential allocation of overt attention towards the semantically related critical object during the encoding phase, i.e., fixation probability. Semantic relatedness affected recollection probability and fixation probability also in older adults, with no difference with the younger group. However, in the older group, the memory advantage for semantically related objects cannot be entirely explained by the fact that participants were more likely to fixate them compared to semantically unrelated ones during the inspection of the arrays, and other cognitive mechanisms should be considered to explain this effect (see next section for a discussion). As for experiment 5, visual saliency had a significant effect neither on recollection probability, nor on eye movements, of both younger and older adults.

5.4 General discussion

In this chapter, I conducted two experiments in which participants were asked to freely inspect object arrays and memorize as many objects as possible for immediate verbal recall. The object arrays displayed a critical object and other objects, i.e., distractors. The critical object was either salient or non-salient, and either semantically related or unrelated to the distractors, which were always semantically related among them. Experiment 5 had young participants performing the memorization task on arrays of different size (3, 5, and 7), and examined the influence of visual saliency and semantic relatedness information on memory, i.e., the probability of recalling the critical object, and their interplay in guiding eye movements. Experiment 6 had both younger and older adults performing the same memorization task on five-object arrays only, with the aim to study age-related differences in the contribution of low-level saliency and high-level semantic information to attention and memory.

Consistently with previous studies showing that semantic relationships among stimuli, both verbal and visual, improve their recall, (Guerin & Miller, 2008; Poirier et al., 2015; Saint-Aubin et al., 2005; Suzin et al., 2019), I found that the critical object was more likely to be recalled when it was semantically related than unrelated to the distractors, in both younger and older adults.

Visual saliency did not affect memory performances, in contrast with previous research on naturalistic scenes showing a memory advantage for salient than non-salient objects (e.g., Pedale & Santangelo, 2015; Santangelo & Macaluso, 2013). There is evidence that the influence of low-level visual saliency on memory increases with increasing task difficulty (Fine & Minnery, 2009). Compared to the object arrays used in the current experiments, naturalistic scenes tend to be more crowded with objects competing among each other for attentional and memory resources. It might be that my task was not very demanding for the participants, especially when it required the memorization of only 3 and 5 objects, and this contributed to the absence of saliency effects (see Pedale & Santangelo, 2015; Santangelo, 2015, for studies supporting this suggestion).

Critically, the prioritisation of semantically related objects in memory could be explained by a preferential allocation of overt attention towards them, as they were more likely to be fixated than semantically unrelated objects during the inspection of the arrays, both by younger and older adults. While the differential allocation of overt attention seems to explain entirely the effect of semantic relatedness on memory for younger adults, this was not the case for older adults. Indeed, in the older group, the analysis of recollection probability showed a significant effect of semantic relatedness even after including fixation probability in the regression model. Other factors may have thus contributed to the semantic relatedness effect on the memory performances of older observers. A plausible mechanism is that of semantic priming, whereby having just retrieved an object might prime the retrieval of a semantically related object (e.g., Cadar et al., 2018). Alternatively, it might be that participants used the semantic category shared by the objects in the arrays as a cue to retrieve information, thus facilitating the recall of the critical object when it was semantically consistent than inconsistent to it (e.g., Guerin & Miller, 2008). Both semantic priming and cued retrieval are known to be preserved in older adults (Badham, Hay, Foxon, Kaur, & Maylor, 2016; Laver & Burke, 1993; Mehta & Jerger, 2014), and seem to have had an active role especially when they tried to recall an object which was not fixated during array inspection, as evidenced by the two-way significant interaction between semantic relatedness and fixation probability on recollection probability.

Visual saliency did not have a significant effect on fixation probability. Also, visual saliency, as well as semantic relatedness, did not influence the time to first fixation and the total fixation duration on the critical object. The failure to find significant effects of visual saliency and semantic information on these measures might have been caused by the time pressure under which participants performed the task. The limited time available to inspect the arrays might have encouraged participants to scan as many objects as they could, as fast as they could, thus diminishing the effects of the visual saliency and semantic features of objects on these time-dependent measures.

All in all, the two experiments presented here showed that the semantic relatedness among objects is an important factor in determining whether they will be remembered or not, and it does so by influencing the allocation of overt attention, in both younger and older observers, thus indicating a strong relationship between objects' features, the allocation of overt attention, and memory.

6 Conclusions

6.1 General aims

Both earlier (Treisman & Gelade, 1980; Treisman & Sato, 1990; J. M. Wolfe, 1994; J. M. Wolfe et al., 1989; J. M. Wolfe & Gancarz, 1996) and more recent models (Itti & Koch, 2000; Parkhurst et al., 2002; Torralba et al., 2006; J. M. Wolfe, 2007; Zelinsky, 2008; Zelinsky et al., 2013) of visual attention attribute a primary role to the low-level, visual features of stimuli, e.g., colour and shape, in guiding eye movements during the inspection of a visual context.

However, real-world objects are defined not only by low-level, visual features, but also by high-level, semantic features, such as their meaning and semantic relationships among them. Over the last 40 years, a lot of studies have examined the role of the semantic features of objects in guiding the allocation of overt attention. More specifically, previous research has investigated several research questions: a) can the semantic features of objects be processed in extra-foveal vision to guide eye movements? and, b) if so, what are the temporal dynamics of such influence?; c) are the extra-foveal semantic processing and the semantic guidance of overt attention preserved in healthy and pathological ageing?; d) do low-level, visual and high-level, semantic information of objects interact in guiding visual attention?; e) how does the interplay between object semantic and visual features change across different visual tasks?. Six experiments were reported in this thesis, aimed to address these questions.

6.2 Overview of the experiments and tasks

A new experimental paradigm was devised for the purpose of this thesis, whereby participants were asked to inspect arrays of objects consisting of a critical object and additional distractor objects, while their eye movements were monitored. The critical object was manipulated so that it was either salient or non-salient, and either semantically related or unrelated to the distractors, which were always semantically related among them.

In Experiments 1 and 2, young adults were instructed to scan object arrays of different sizes, i.e., 3, 5, and 7 objects, while searching for a target specified by a verbal label, presented at the beginning of search. The label cued the critical object as the search target (target-present trials), or as a target's semantically related distractor (target-absent trials). The two experiments tested whether the semantic features of objects could be processed early, and in parallel, in extra-foveal vision, and guide initial eye movements. I expected early overt attention to be preferentially directed towards the critical object when semantically unrelated than related to the distractors, across arrays of different sizes. In fact, in the semantically unrelated condition, the critical object was the only object sharing semantic features with the target, whereas in the related condition, all the objects were potential targets and equally competed for visual attention.

In Experiments 3 and 4, healthy older adults and AD patients were asked to perform the same visual search task on five-object arrays only. I examined their eye-movement behaviour with the hypothesis that if the processing of object semantic information was preserved in these groups of participants, then it should have mediated the allocation of overt attention.

In Experiments 5 and 6, younger and older adults were presented with the same object arrays, but this time, they were asked to inspect them in preparation for an immediate verbal recall task. I examined the interplay of visual saliency and semantic information in guiding eye movements towards the critical object, and whether the pattern of eye movements could explain memory performances.

6.3 Overview of the main findings, related theoretical implications, and indications for future studies

Experiments 1 and 2 showed that the critical object was looked at earlier when it was semantically unrelated than related to the distractors, since the very first fixation after the onset of the search array. This finding indicates that object semantic information can be extracted rapidly in extra-foveal vision to guide early overt attention. Visual saliency did not exert any influence on overt attention, in line with previous research on visual search on object arrays (Chen & Zelinsky, 2006). Also, visual similarity, which is known to play a primary role in search guidance (e.g., Alexander & Zelinsky, 2011; J. Schmidt & Zelinsky, 2009), predominant over that of semantic relatedness (de Groot et al., 2016; Nuthmann et al., 2019), did not have any significant main effect on eye movements. I posit that my experimental design, with all the distractors semantically related among each other, may have boosted the guidance of overt attention exerted by object semantic features over that of visual features (Duncan & Humphreys, 1989). Future research is needed to better describe how the semantic relatedness between distractors would impact on visual search, for example, by systematically varying their semantic relatedness on a continuum, i.e., from distractors all semantically homogeneous (i.e., the current study) to distractors that are all heterogeneous.

The effect of semantic relatedness on initial eye movements was consistently found for increasing set sizes, and did not decrease when the number of objects on the array increased. However, I also observed that increasing the set size reduced the probability of first fixation to the critical object overall, both when it was semantically unrelated and related to the distractors. I interpreted these findings by suggesting that some parallel processing of object semantics occurred (see Buetti et al., 2016). However, as semantic information may be only partially acquired in extra-foveal vision (Gordon, 2004), such processing may be limited in nature. Further evidence that the semantic information of more than a single object was accessed early in extra-foveal vision comes from the data on the first-gaze duration on the critical object. This was looked at for the first time less when it was semantically related than unrelated to the distractors, also when it was the first object to be fixated.

These findings pose a challenge to current models of visual attention which assume that overt attention is purely guided by the extra-foveal and parallel processing of low-level visual features of stimuli, and support the inclusion of the semantic features of objects as important information available to observers to guide attention. Future models of visual attention should consider these findings. The extra-foveal semantic processing might rely on a global deployment of covert attention, i.e., distributed attention, occurring across the visual field (Treisman, 2006). Such processing eases a rapid extraction of the general layout of the information within the context, i.e., its gist, as well as the objects therein, including some summary statistics, i.e., ensemble perception (see Whitney & Leib, 2018, for a recent review); both in naturalistic scenes (Davenport, 2007; Davenport & Potter, 2004; Gordon, 2004) and object arrays (Auckland et al., 2007; Starreveld, Theeuwes, & Mortier, 2004). Alternatively, observers might be able to access partial semantic information of an object, such as its category membership, through a rapid and parallel processing of disjunctive sets of visual features characterizing that category (Evans & Treisman, 2005), which would occur pre-attentively across the visual field (Treisman, 2006; see also J. M. Wolfe & Utochkin, 2019, for a very recent discussion about pre-attentive features). For example, observers might detect the presence of a four-footed animal by using specific feature detectors: eyes, a set of legs, head, fur. These feature detectors would mediate the classification/categorization of both natural (e.g., animal) and non-natural (e.g., vehicle) objects but not their full identification, which would still require the serial deployment of overt attention to bind their features together.

It is important to note that these findings do not necessarily extend to search in naturalistic scenes, which vary along a wider range of low- and high-level features than object arrays. For example, objects in a naturalistic scene (e.g., a restaurant) are usually arranged according to semantic (e.g., a chair is a common object in a restaurant scene, whereas a bed would be inconsistent with it) and syntactic (e.g., a chair does not fly) information (Biederman, 1976; Draschkow & Võ, 2017; J. M. Wolfe, Võ, Evans, & Greene, 2011). Moreover, in a single glance, observers can pre-attentively accrue a considerable amount of global information about a scene (e.g., the scene gist, Greene & Oliva, 2009; Oliva & Torralba, 2006). Observers may therefore integrate object-specific information with global scene information to optimise search (Castelhano & Heaven, 2011; Castelhano & Henderson, 2007; Malcolm & Henderson, 2010; Neider & Zelinsky, 2006); but see Greene and J. M. Wolfe (2011) showing that global scene information does not seem to improve visual search. Moreover, the position of an object relative to the centre of the screen, as well as the global and local crowding surrounding it, may reduce its extra-foveal processing (Pelli et al., 2004; Pelli & Tillman, 2008; Rosenholtz, 2016). Further research is needed to investigate, more systematically, the low- and high-level features that are truly processed in extra-foveal vision regardless of whether the visual context is an object array or a naturalistic scene.

Having established the efficiency of the semantic manipulation on younger adults, I conducted Experiment 3, which had younger and healthy older adults performing the same visual search task. In this experiment, the analysis of standardised search latency showed that the critical object was fixated earlier when it was semantically unrelated than related to the distractors, in both the younger and older group, with no difference among them (no significant semantic relatedness x group interaction). This finding indicates that, similarly to younger adults, older adults process object semantic information in extra-foveal vision to guide overt attention. However, the lack of semantic relatedness effects on the probability of immediate fixation in the older group points to some age-related differences in the time course of such processing. Collectively, my findings support the hypothesis that a major factor contributing to age-related performance differences is the generalized cognitive slowing associated with ageing (Salthouse, 1996, 2012). Older adults would need more time than younger adults to execute relevant operations, e.g., visual information processing (Owsley, McGwin, & Searcey, 2013), necessary to complete a task, e.g., searching for target objects among distractors (Muiños & Ballesteros, 2014; Muiños et al., 2016). If timing is truly a crucial factor in the occurrence of semantic influences on attentional guidance of older observers, an interesting question for future studies is how much time would be needed to attenuate the age-related slowing of cognitive processing, thus increasing the probability to find semantic relatedness effects on initial eye movements also in older adults. If older adults were asked to look at the centre of the display for a progressively increasing amount of time (e.g., 50, 100, 200, 500 ms) before launching the first saccade towards the objects in the arrays, at what point would we observe evidence of semantic guidance of early overt attention?.

In Experiment 4, I used the same visual search task to compare the eye-movement responses of AD patients and age-matched healthy controls. When looking at the standardised search latency, I found that both groups looked at the critical object earlier in the semantically unrelated compared to the related condition. The effect of semantic relatedness did not differ across groups. This outcome provides evidence of extra-foveal processing of object semantics and critically highlights that this mechanism is preserved in AD. The evidence of preserved extra-foveal semantic processing indicates the AD does not entail a complete loss of semantic knowledge, as suggested by previous studies using different research paradigms (Adlam et al., 2006; Hodges et al., 1992; Salmon et al., 1999). AD patients may be able to process and efficiently use semantic information to perform a task when it involves implicit memory and automatic processing (Chertkow et al., 1994; Hernández et al., 2008; Nakamura et al., 2000), as in my visual search task. Also, my task used non-verbal stimuli, which might have enabled AD patients to access semantic information more easily compared to when verbal stimuli are used (Ally, Gold, et al., 2009; Rich et al., 2002). Future research may employ the same visual search experimental paradigm used here but with verbal material, i.e., searching for a word (related or unrelated) in an array of semantically related words. Such a study may help to shed light on the role played by the stimulus material in semantic information processing in AD.

Experiments 5 and 6 used the same object arrays as in the previous experiments, but had younger and older participants to freely inspect them, in preparation for later verbal recall. I found that, during the inspection of the object array, the critical object was more likely to be fixated when it was semantically related than unrelated to the distractors. This result indicates that during memorization, overt attention is guided by the extra-foveal analysis of the semantic features that are shared between the objects in a visual context, thus extending our finding from the visual search task experiments to a memorization task (see also Suzin et al., 2019, for similar findings from a recent eye-tracking study). That being said, semantic relatedness did not affect any other eye-movement measures, i.e., time to first fixation and total fixation duration, as well as visual saliency. I argue that the lack of significant effects of visual saliency on eye movements and of semantic relatedness on time-dependent measures might have been caused by characteristics of the experimental design, e.g., the limited time available to memorize the objects.

The preferential allocation of overt attention towards semantically related objects strongly contributed to their ability to be encoded and stored in memory. Semantically related objects were more likely to be recalled than unrelated objects, and this difference can be entirely attributed to differences in the fixation patterns for the objects as a function of their semantic relatedness, at least for younger adults. Also, in older adults I found evidence for a strong link between overt attention and memorization; however, beyond the differential allocation of overt attention, a retrieval benefit, e.g., semantic priming, may in part explain their memory advantage for semantically related objects.

All in all, the experiments presented in this thesis highlight the strong and predominant role that extra-foveal semantic processing plays in the guidance of overt attention in different tasks, beyond the influence of other factors, i.e., visual saliency and visual similarity. Thus, my work critically contributes to the debate around the influence of object semantics on eye movement guidance.

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8 Supplemental materials

Supplemental materials A – Miniatures of the experimental arrays

Figure A1. Three-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and non-salient conditions (16 arrays out of 32; used in Experiments 1, 2, and 5).

Figure A2. Three-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and non-salient conditions (32 arrays out of 32; used in Experiments 1, 2, and 5).

Figure A3. Three-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and non-salient conditions (16 arrays out of 32; used for Experiments 1, 2, and 5).

Figure A4. Three-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and non-salient conditions (32 arrays out of 32; used in Experiments 1, 2, and 5).

Figure A5. Three-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and salient conditions (16 arrays out of 32; used in Experiments 1, 2, and 5).

Figure A6. Three-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and salient conditions (32 arrays out of 32; used in Experiments 1, 2, and 5).

Figure A7. Three-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and salient conditions (16 arrays out of 32; used in Experiments 1, 2 and 5).

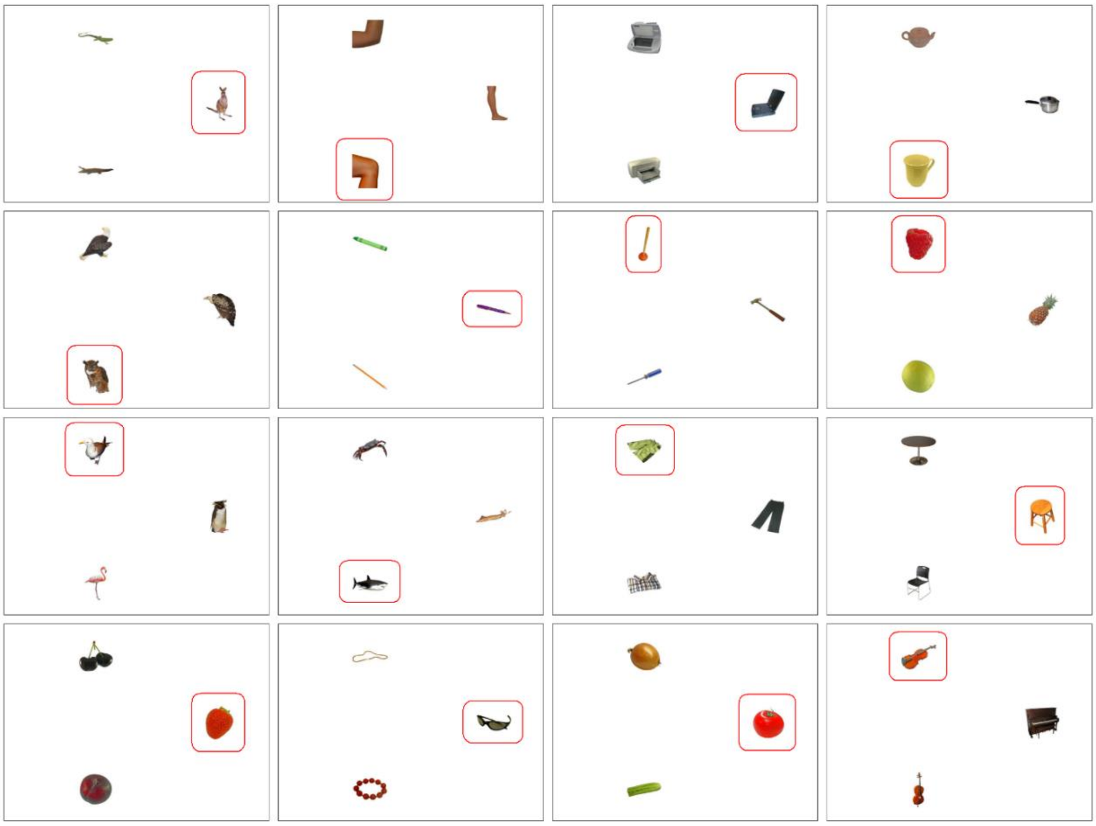

Figure A8. Three-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and salient conditions (32 arrays out of 32; used in Experiments 1, 2, and 5).

Figure A9. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and non-salient conditions (16 arrays out of 40; used in all the experiments).

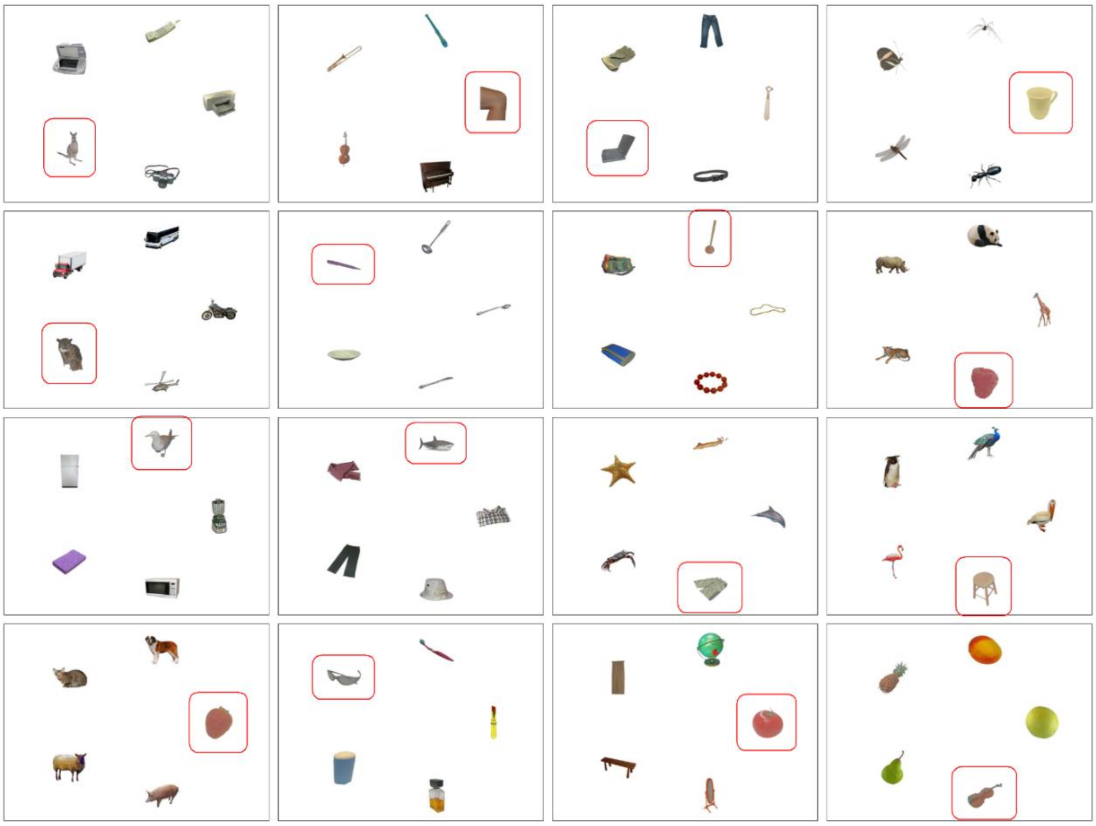

Figure A10. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and non-salient conditions (32 arrays out of 40; used in all the experiments).

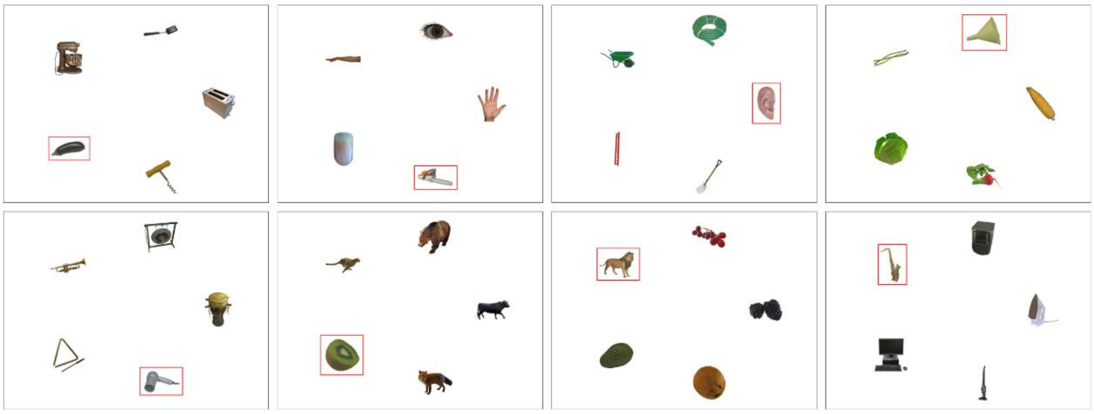

Figure A11. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and non-salient conditions (40 arrays out of 40; used in Experiments 3, 4, and 6).

Figure A12. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and non-salient conditions (16 arrays out of 40; used in all the experiments).

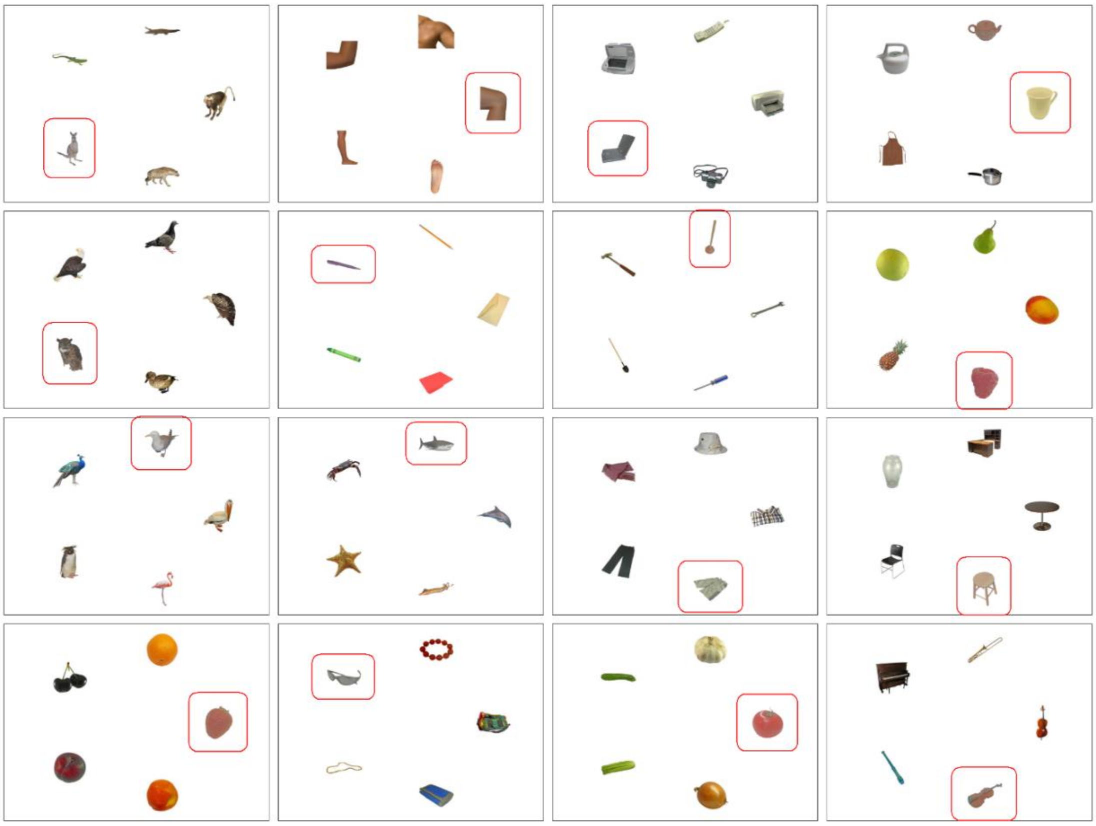

Figure A13. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and non-salient conditions (32 arrays out of 40; used in all the experiments).

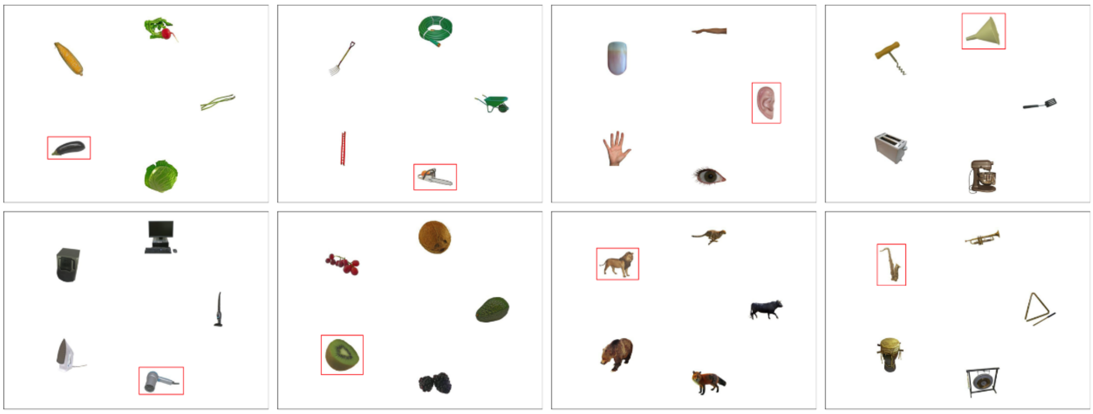

Figure A14. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and non-salient conditions (40 arrays out of 40; used in Experiments 3, 4, and 6).

Figure A15. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and salient conditions (16 arrays out of 40; used in all the experiments).

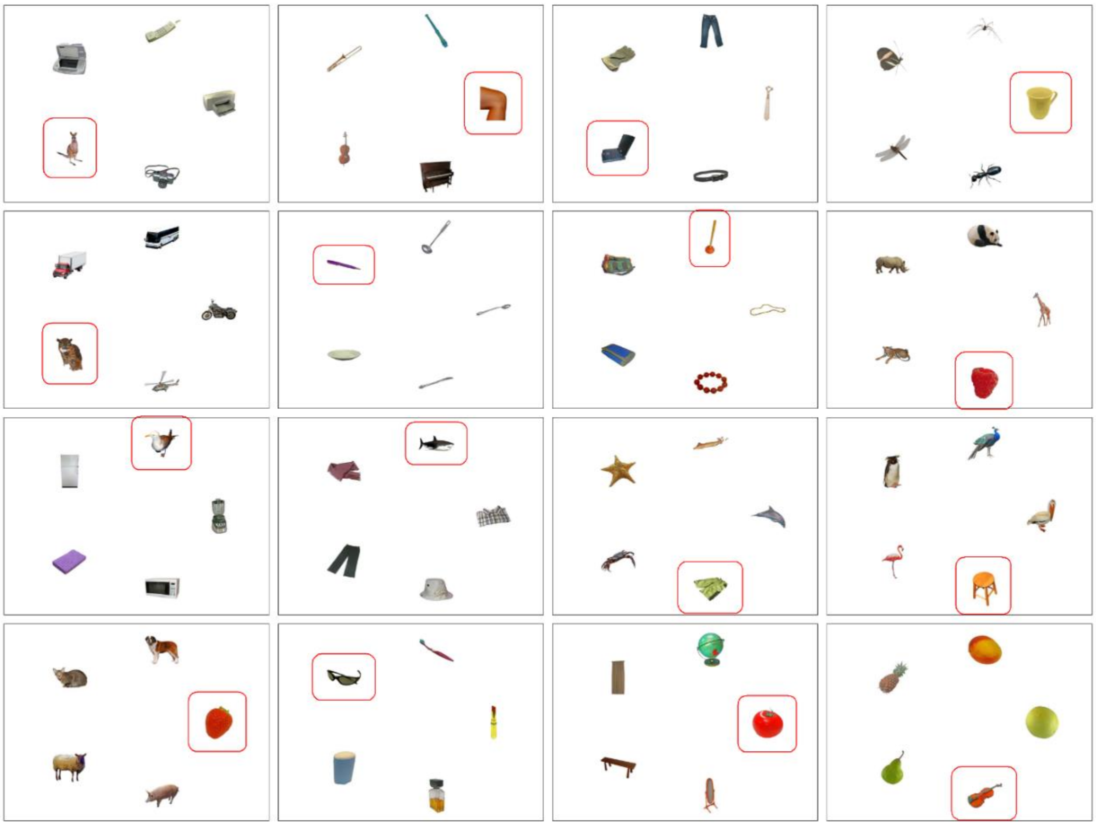

Figure A16. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and salient conditions (32 arrays out of 40; used in all the experiments).

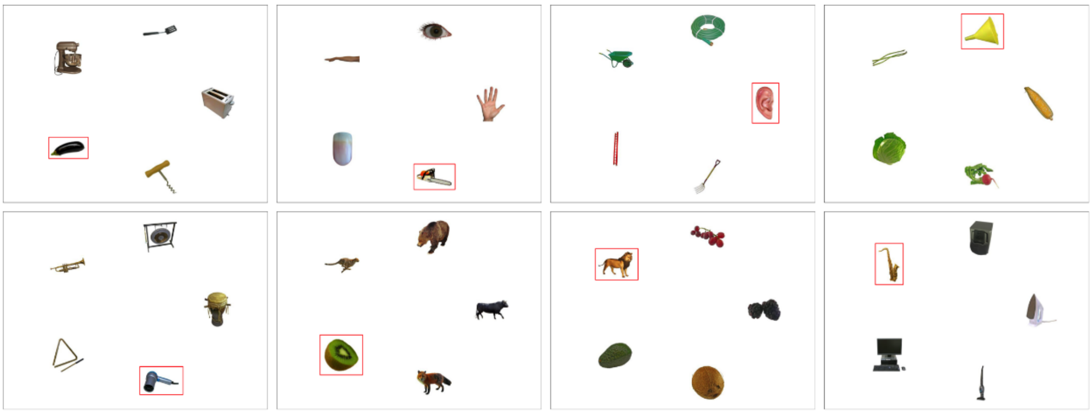

Figure A17. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and salient conditions (40 arrays out of 40; used in Experiments 3, 4, and 6).

Figure A18. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and salient conditions (16 arrays out of 40; used in all the experiments).

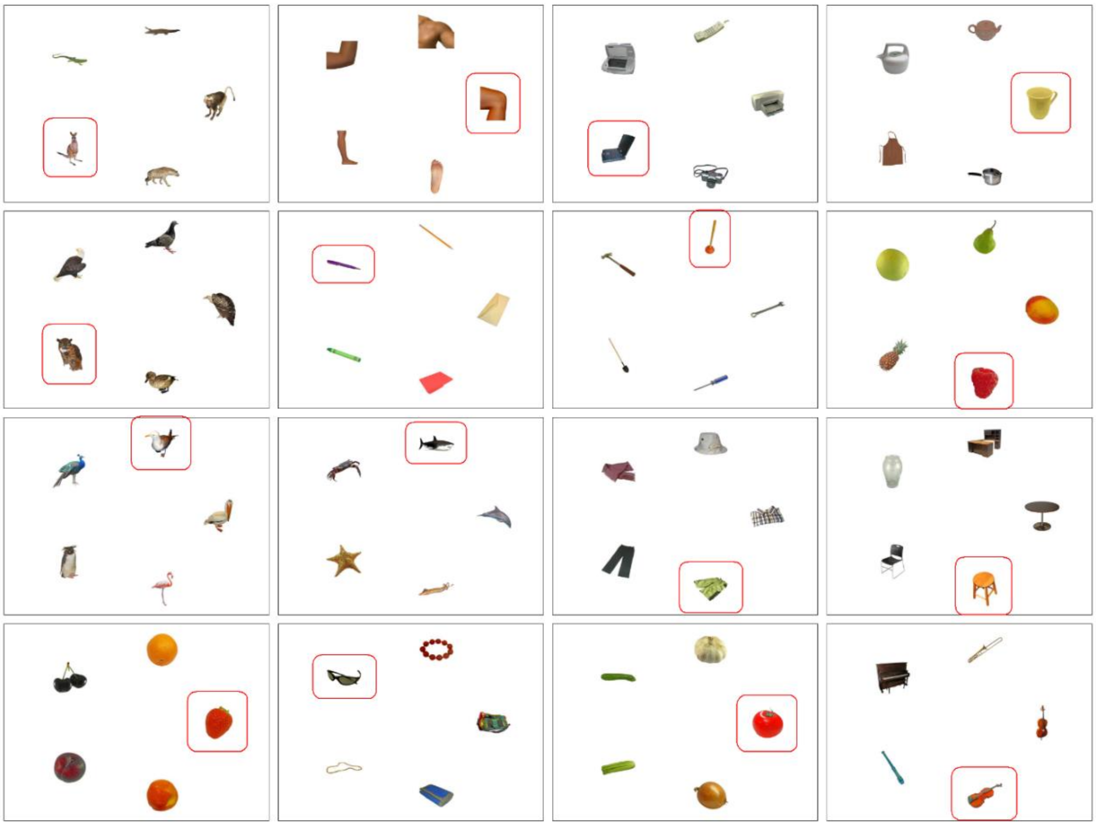

Figure A19. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and salient conditions (32 arrays out of 40; used in all the experiments).

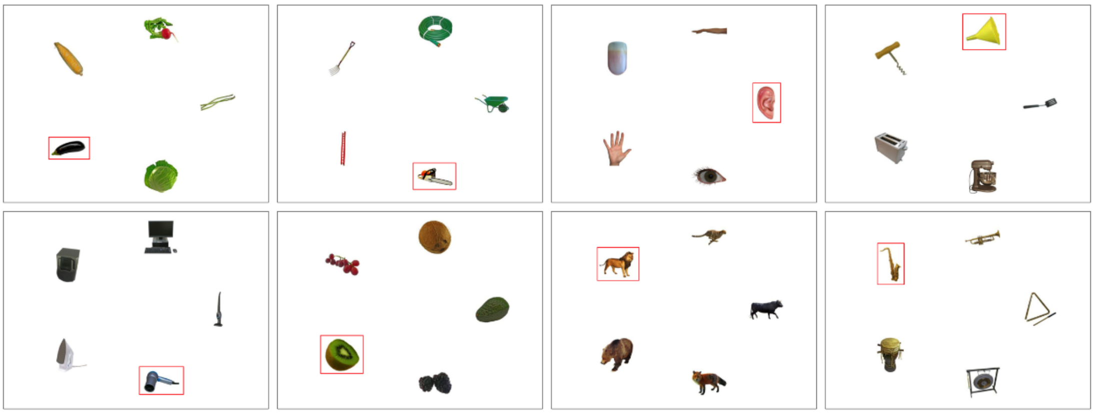

Figure A20. Five-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and salient conditions (40 arrays out of 40; used in Experiments 3, 4, 6).

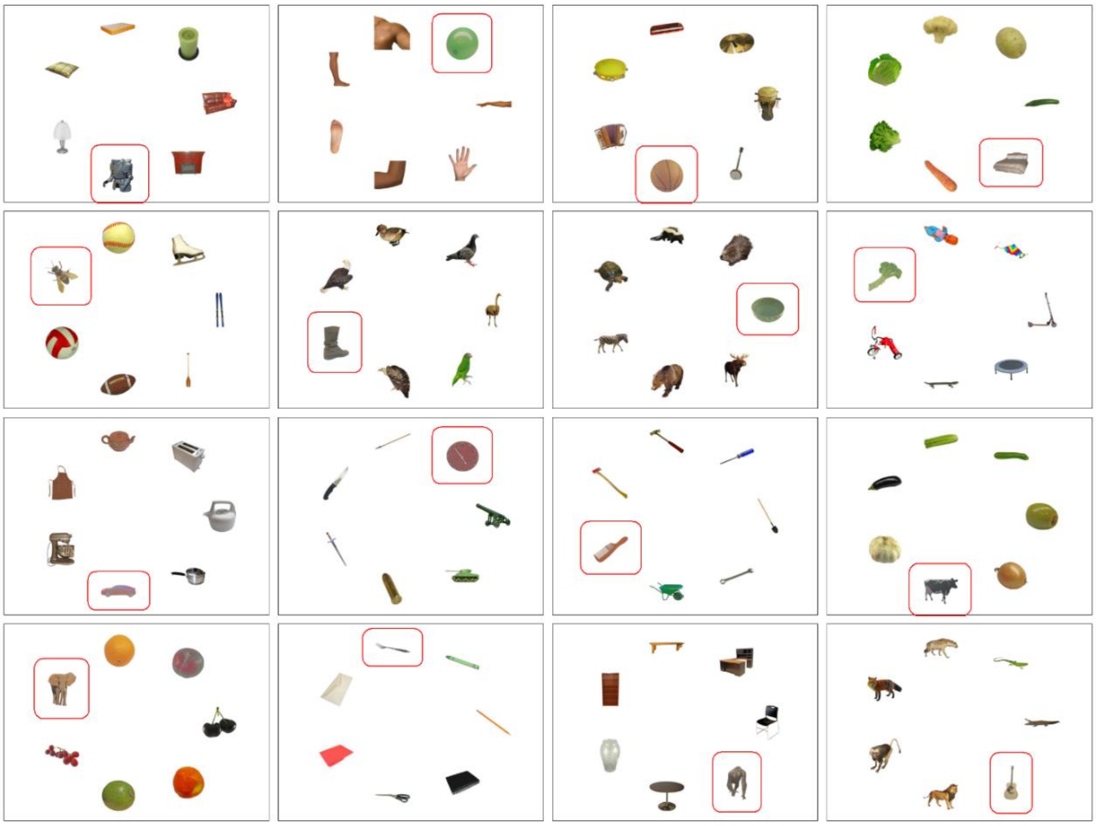

Figure A21. Seven-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and non-salient conditions (16 arrays out of 32; used in Experiments 1, 2, 5).

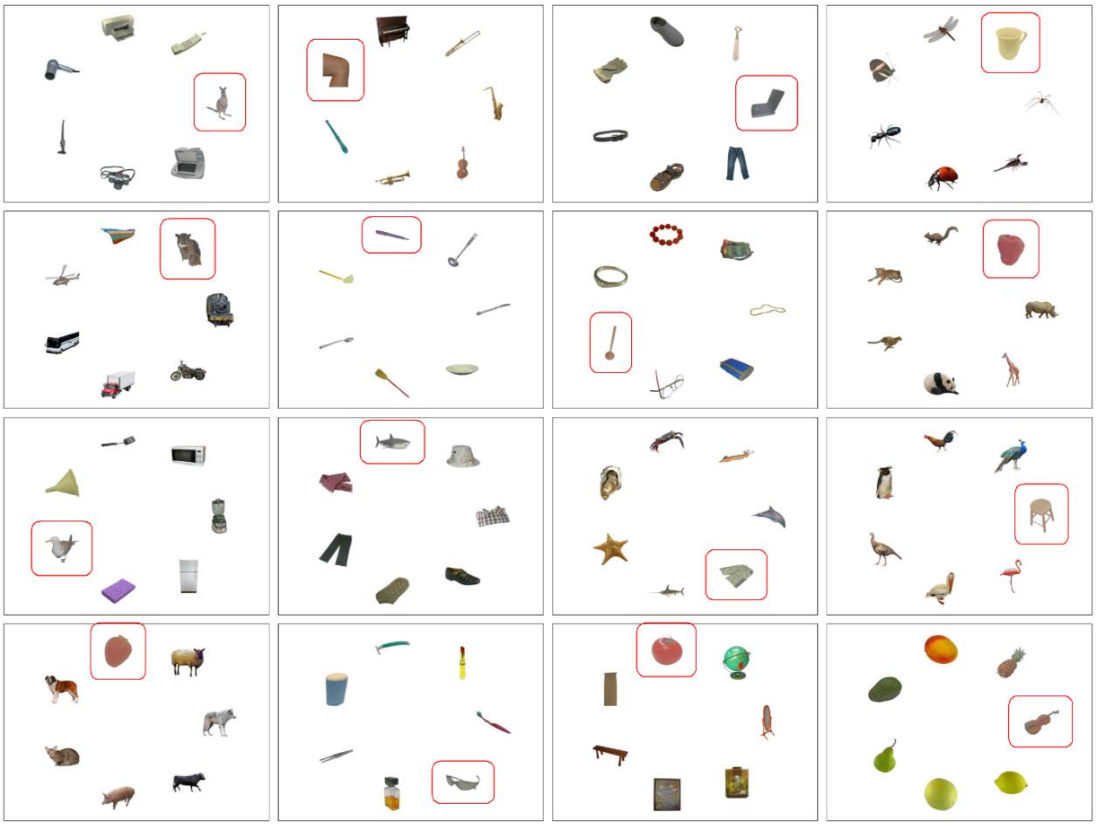

Figure A22. Seven-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and non-salient conditions (32 arrays out of 32; used in Experiments 1, 2, and 5).

Figure A23. Seven-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and non-salient conditions (16 arrays out of 32; used in Experiments 1, 2, and 5).

Figure A24. Seven-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and non-salient conditions (32 arrays out of 32; used in Experiments 1, 2, and 5).

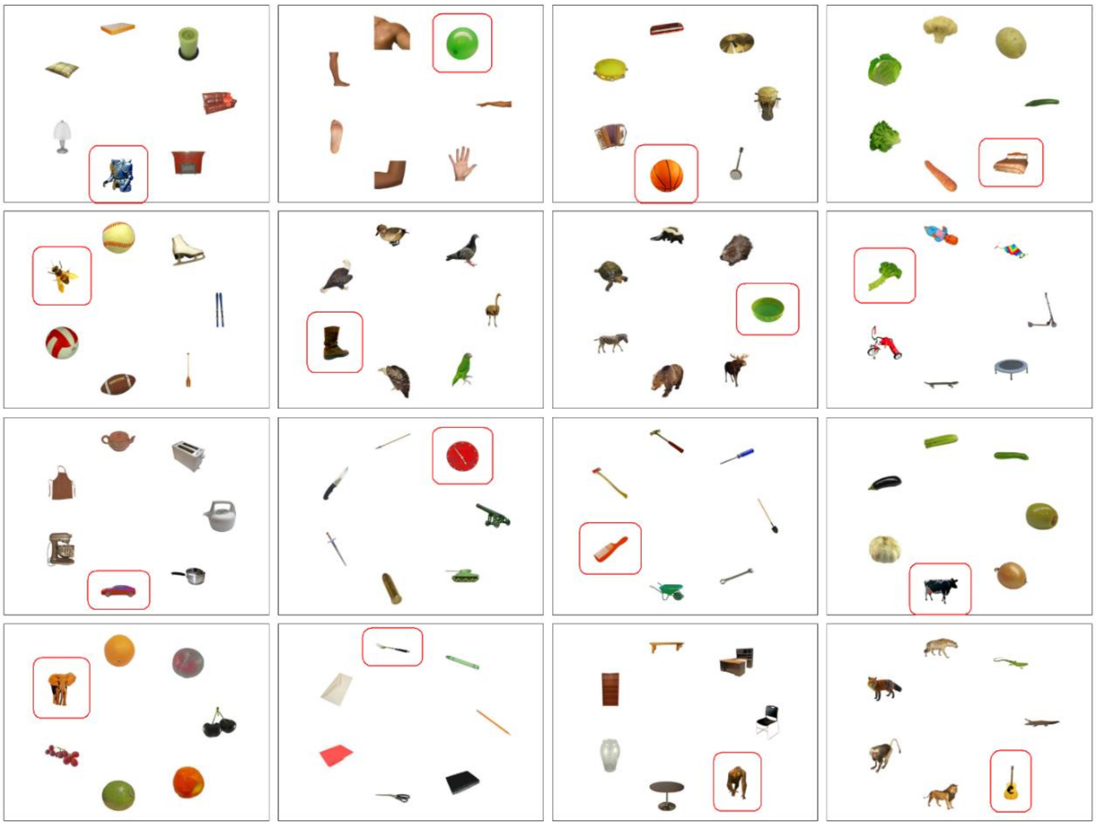

Figure A25. Seven-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and salient conditions (16 arrays out of 32; used in Experiments 1, 2, and 5).

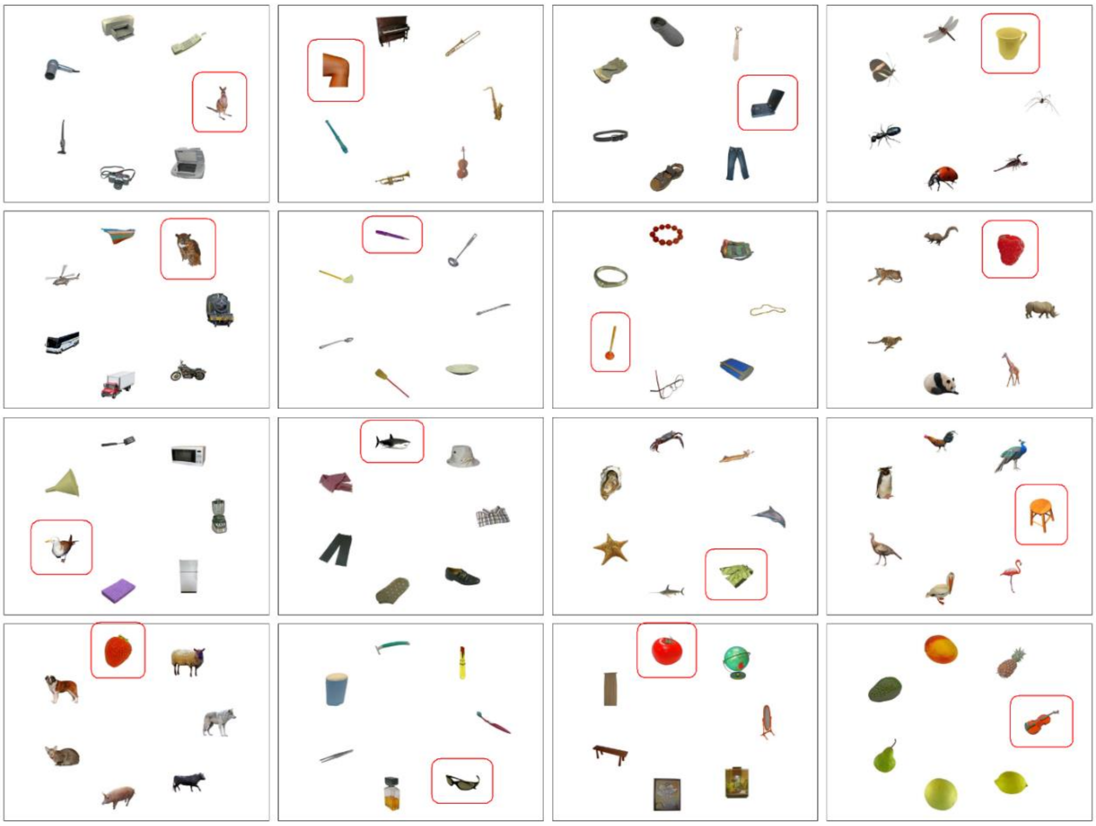

Figure A26. Seven-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the unrelated and salient conditions (32 arrays out of 32; used in Experiments 1, 2, and 5).

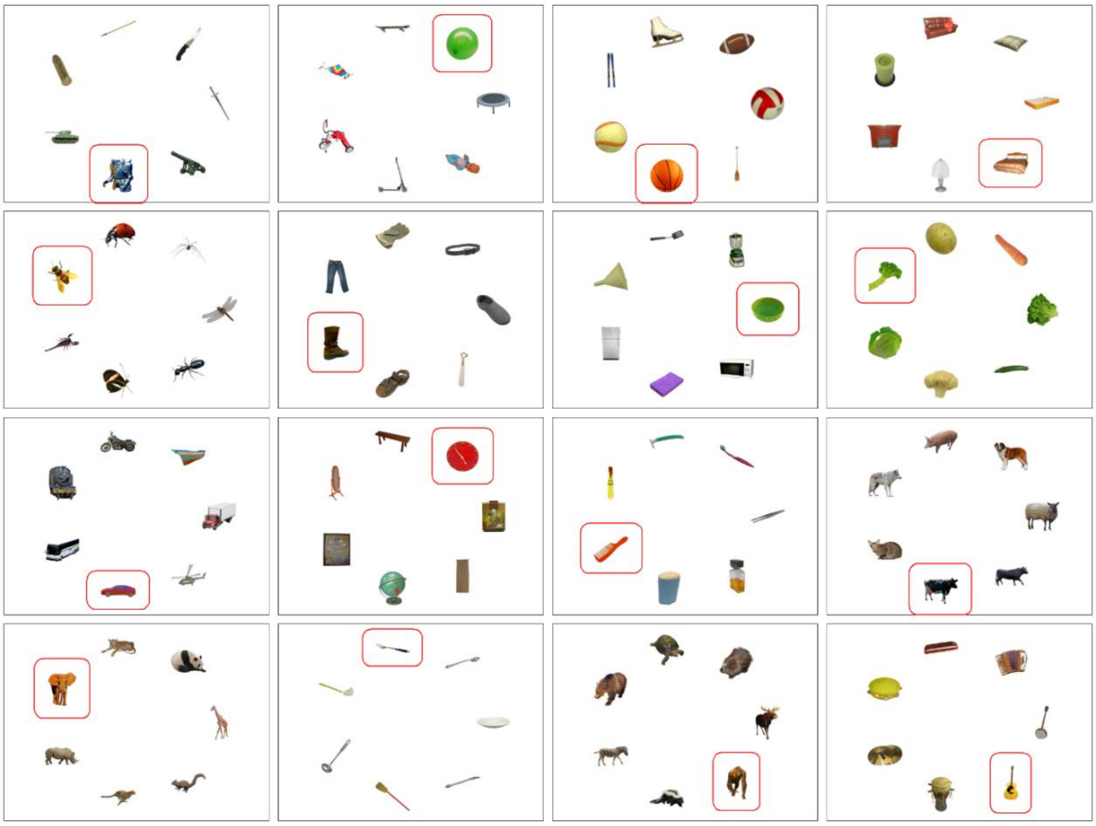

Figure A27. Seven-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and salient conditions (16 arrays out of 32; used in Experiments 1, 2, and 5).

Figure A28. Seven-object experimental arrays with the critical objects (surrounded by their bounding boxes, in red) and distractors in the related and salient conditions (32 arrays out of 32; used in Experiments 1, 2, and 5).

Supplemental materials B – Plotting significant and non-significant predictors

Experiment 1

The independent variables plotted are: Set Size (3, 5, 7), on the left, central, and right panel, respectively; Visual Similarity (Dissimilar, Similar), arranged over the rows of the panels; Visual Saliency (Non-salient, Salient), arranged on the x-axis; and Semantic Relatedness (Unrelated, Related), marked using colour: dark grey and light grey, respectively. Error bars represent 95% confidence intervals around the mean.

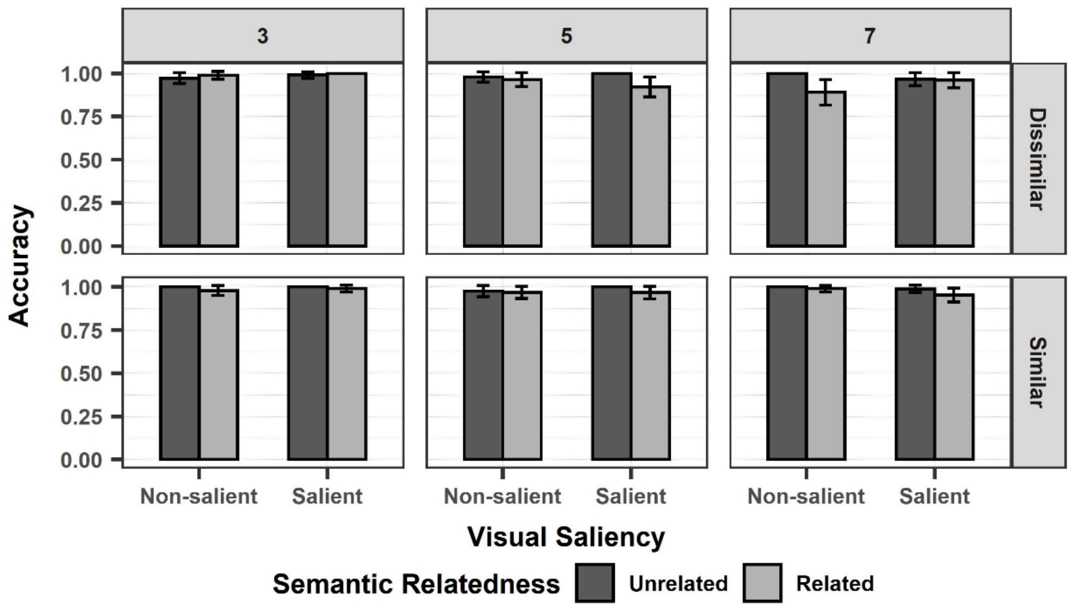

Figure B1. Mean response accuracy (proportions).

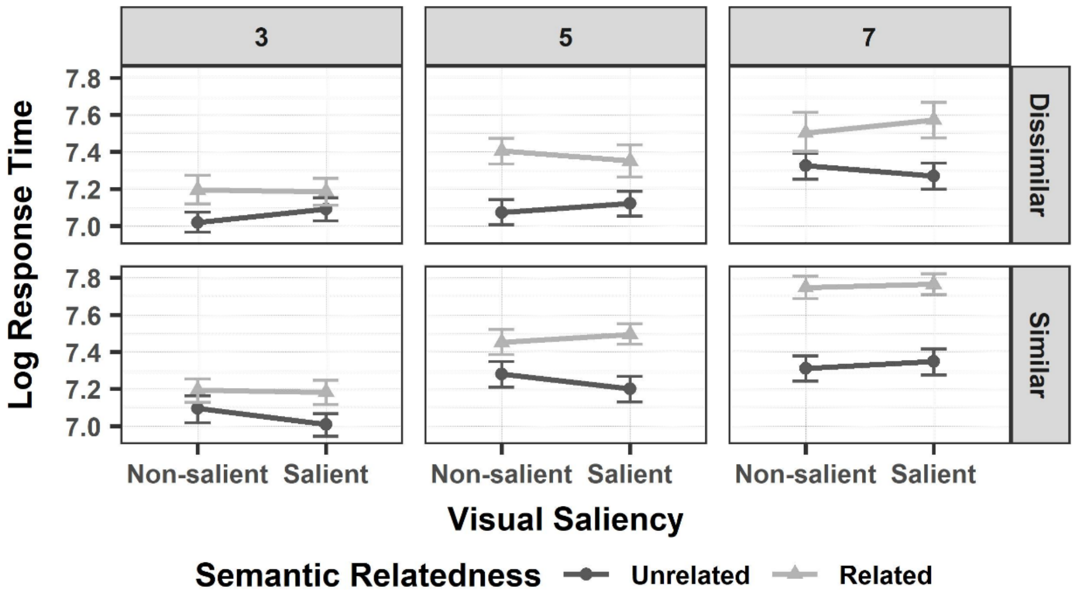

Figure B2. Mean response time (natural-log scale).

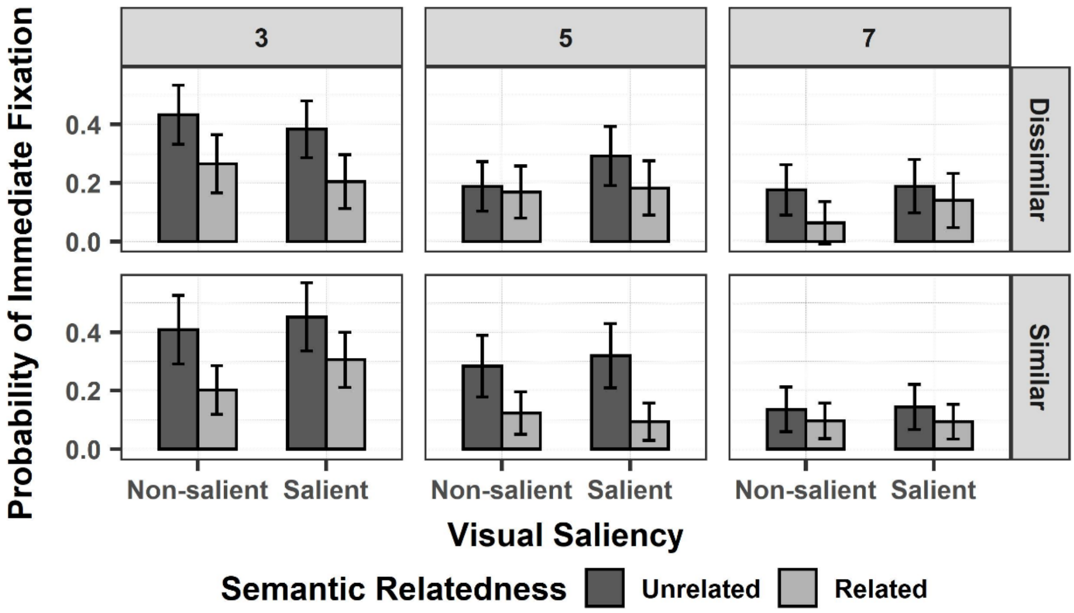

Figure B3. Mean probability of immediate fixation to the critical object (proportions).

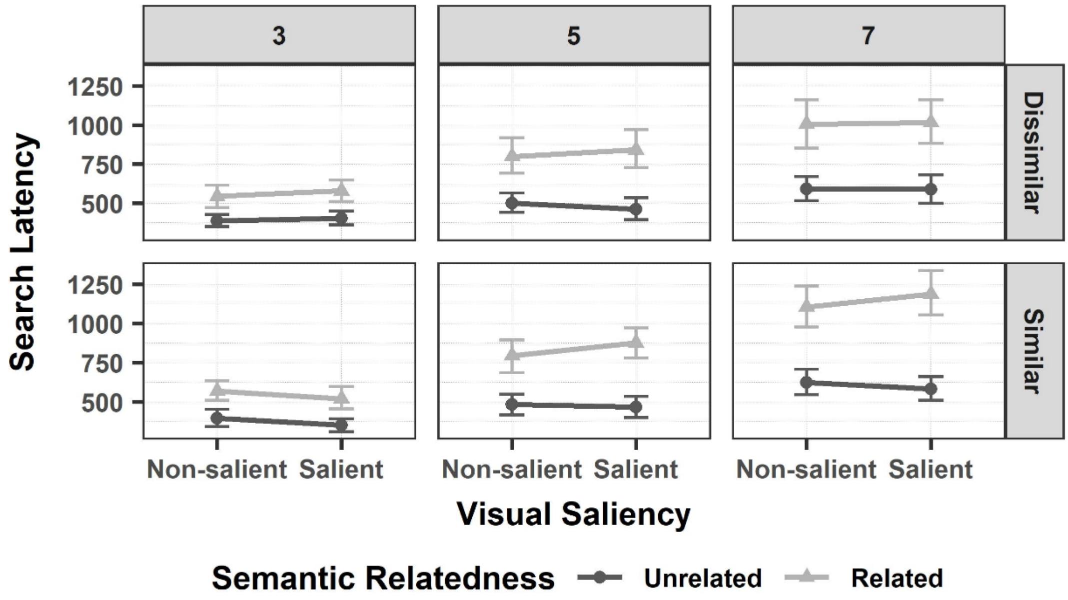

Figure B4. Mean search latency (ms) on the critical object.

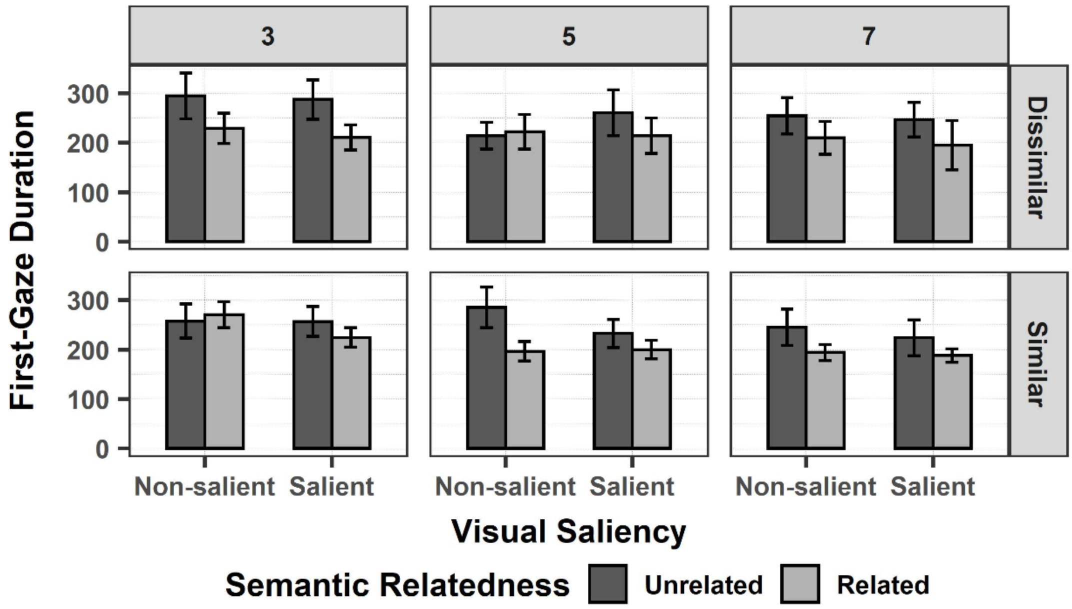

Figure B5. Mean first-gaze duration (ms) on the critical object.

Experiment 2

The independent variables plotted are: Set Size (3, 5, 7), on the left, central, and right panel, respectively; Visual Similarity (Dissimilar, Similar), arranged over the rows of the panels; Visual Saliency (Non-salient, Salient), arranged on the x-axis; and Semantic Relatedness (Unrelated, Related), marked using colour: dark grey and light grey, respectively. Error bars represent 95% confidence intervals around the mean.

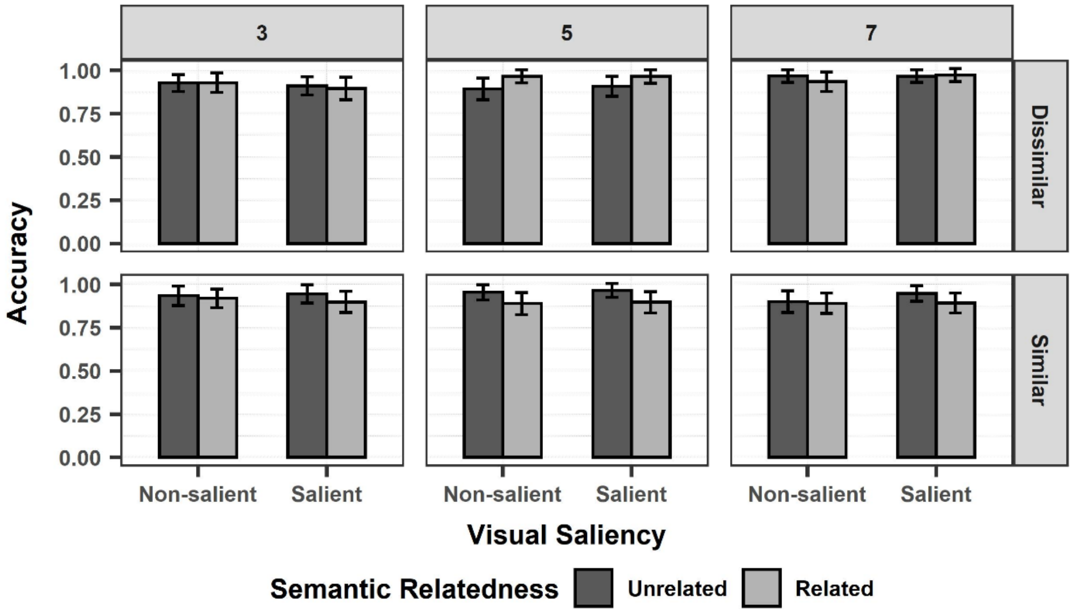

Figure B6. Mean response accuracy (proportions).

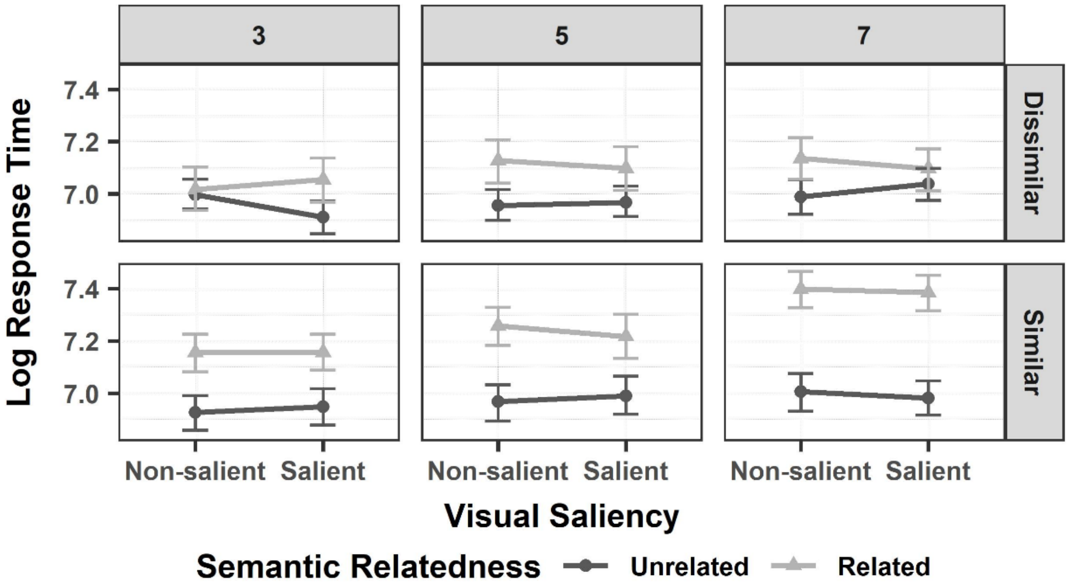

Figure B7. Mean response time (natural-log scale).

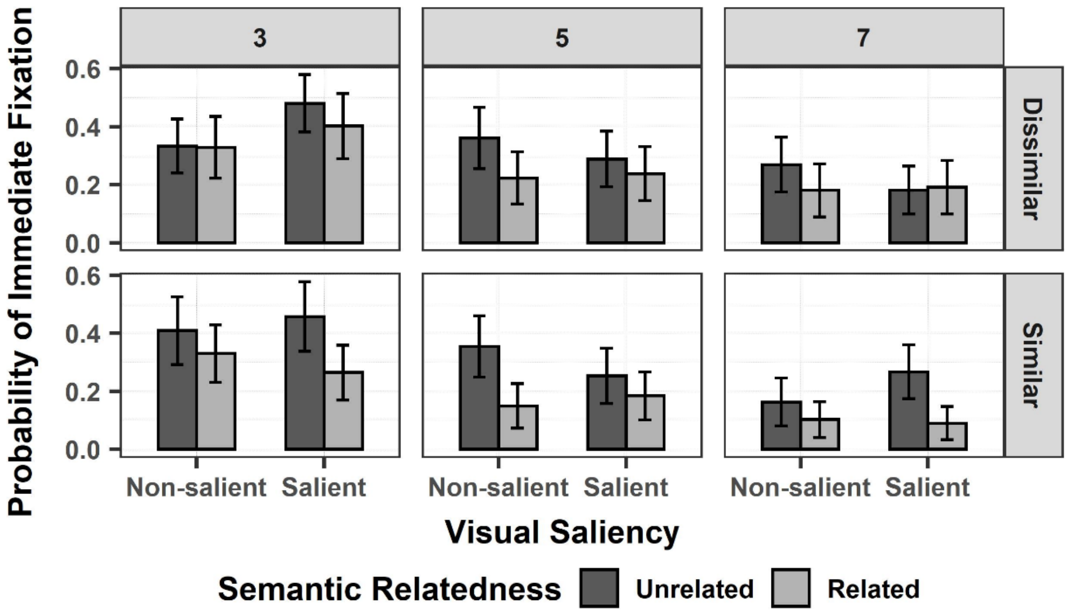

Figure B8. Mean probability of immediate fixation to the critical object (proportions).

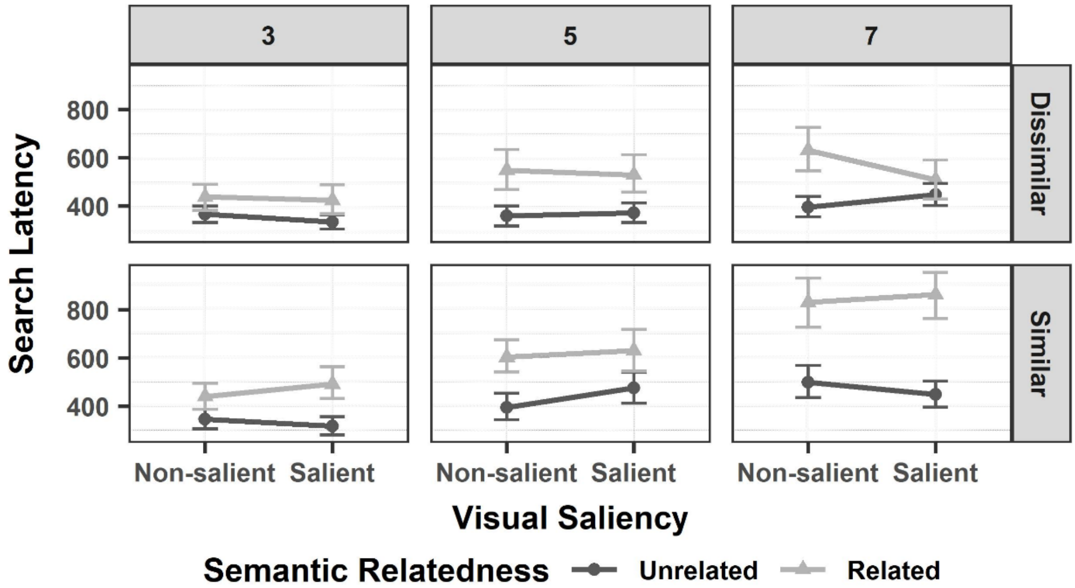

Figure B9. Mean search latency (ms) on the critical object.

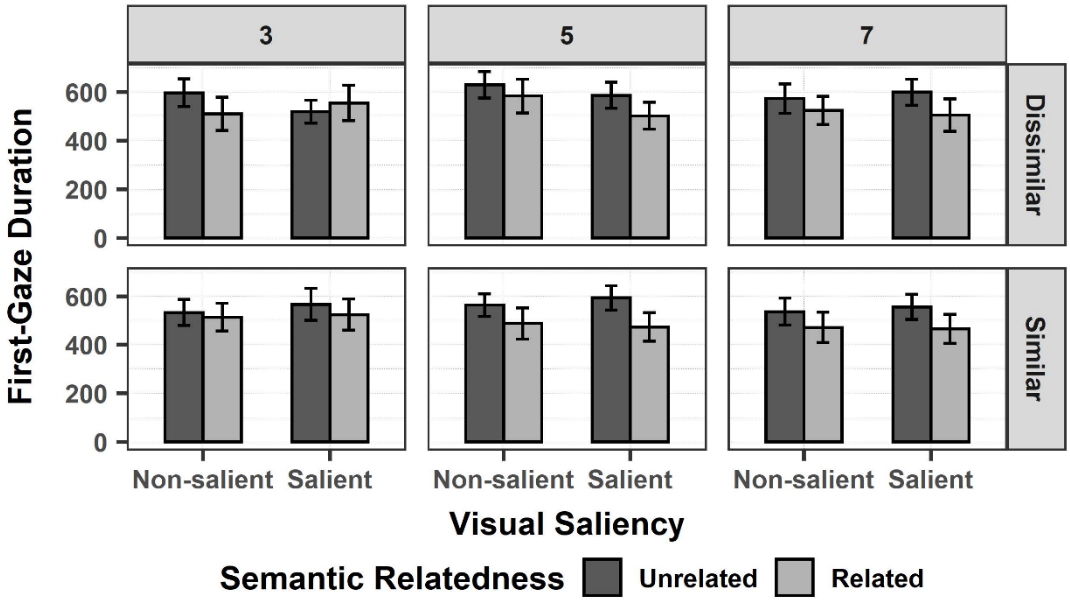

Figure B10. Mean first-gaze duration (ms) on the critical object.

Experiment 3

The independent variables plotted are: Group (younger, older), on the left and right panel, respectively; Target (Absent, Present), arranged over the rows of the panels; Visual Saliency (Non-salient, Salient), arranged on the x-axis; and Semantic Relatedness (Unrelated, Related), marked using colour: dark grey and light grey, respectively. Visual Similarity (Dissimilar, Similar) is not plotted. Error bars represent 95% confidence intervals around the mean.

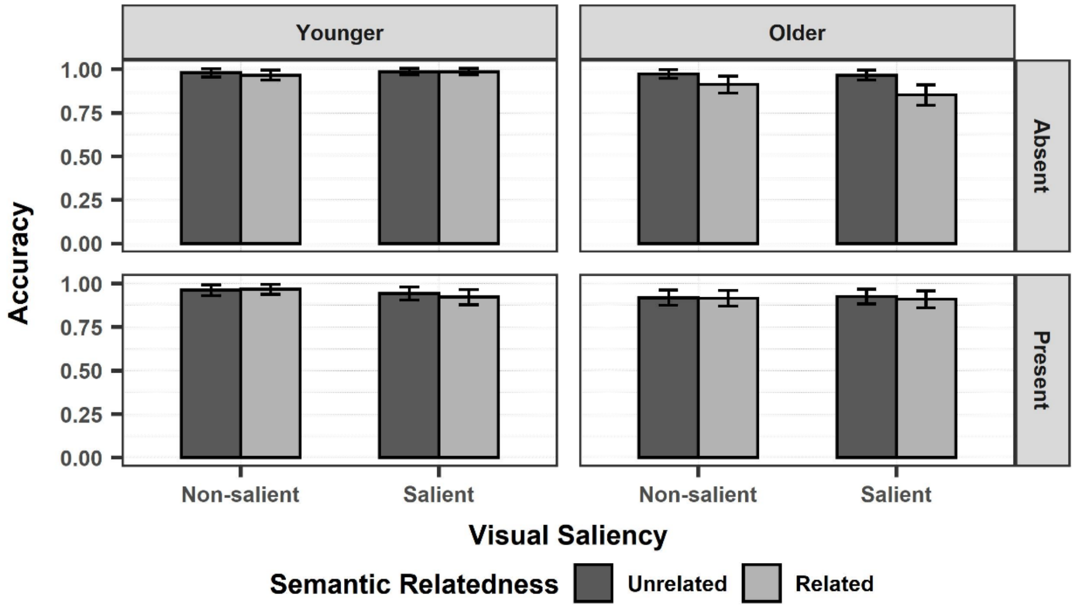

Figure B11. Mean response accuracy (proportions).

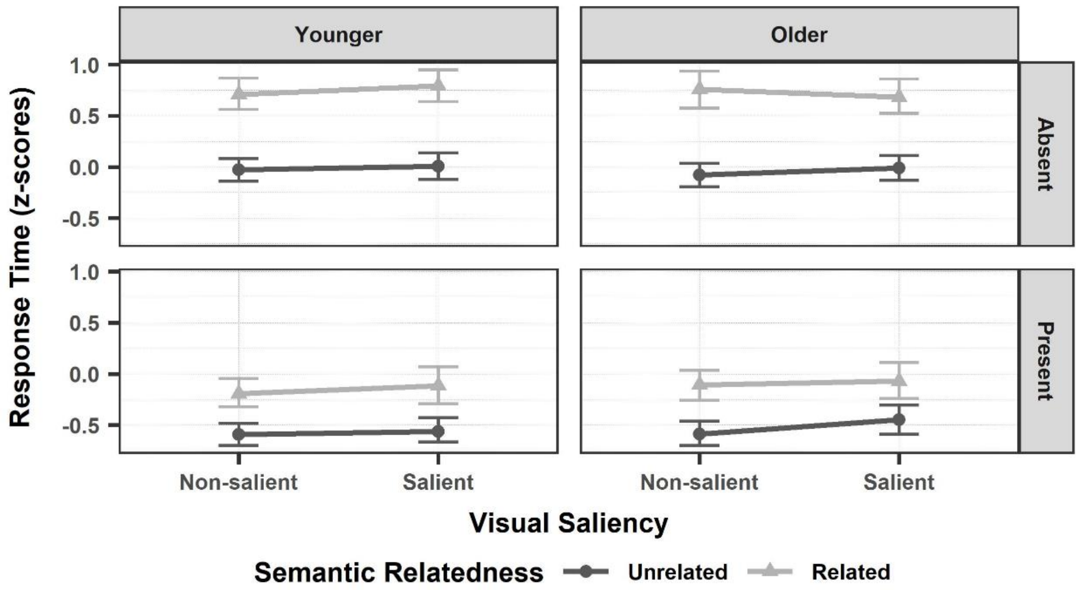

Figure B12. Mean response time (z-scores).

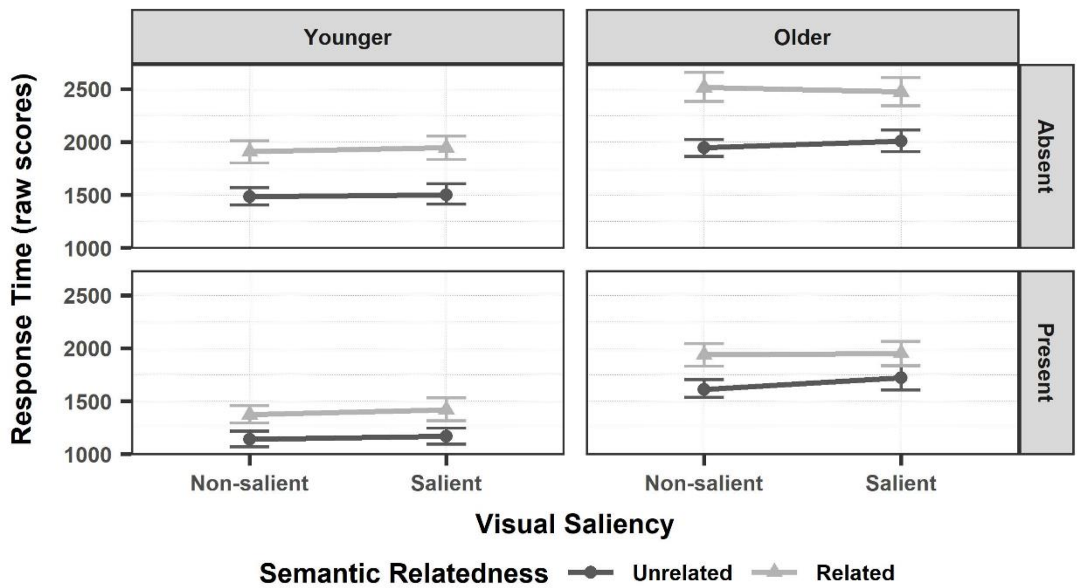

Figure B13. Mean response time (raw scores, ms).

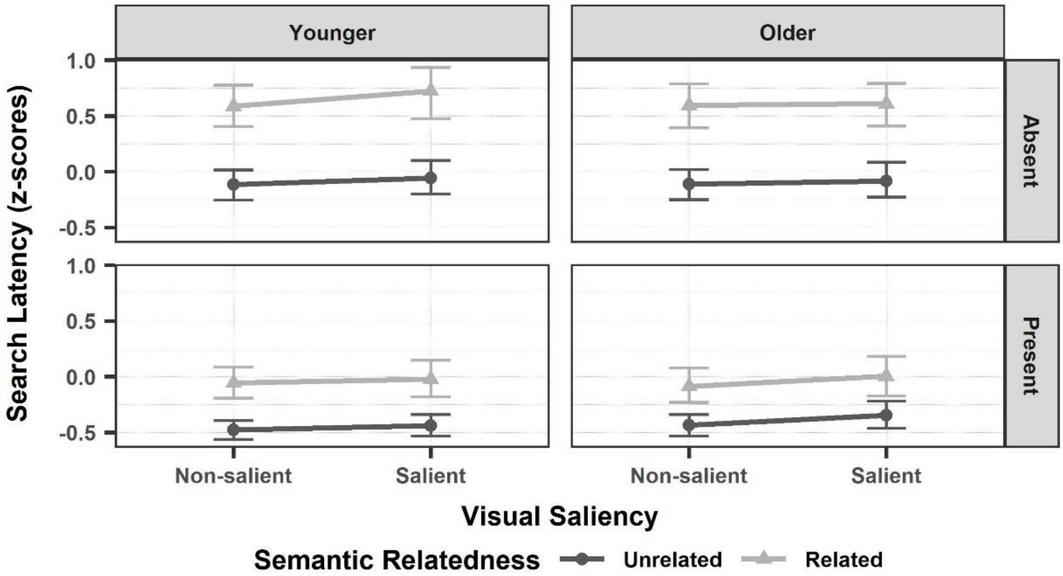

Figure B14. Mean search latency (z-scores) on the critical object.

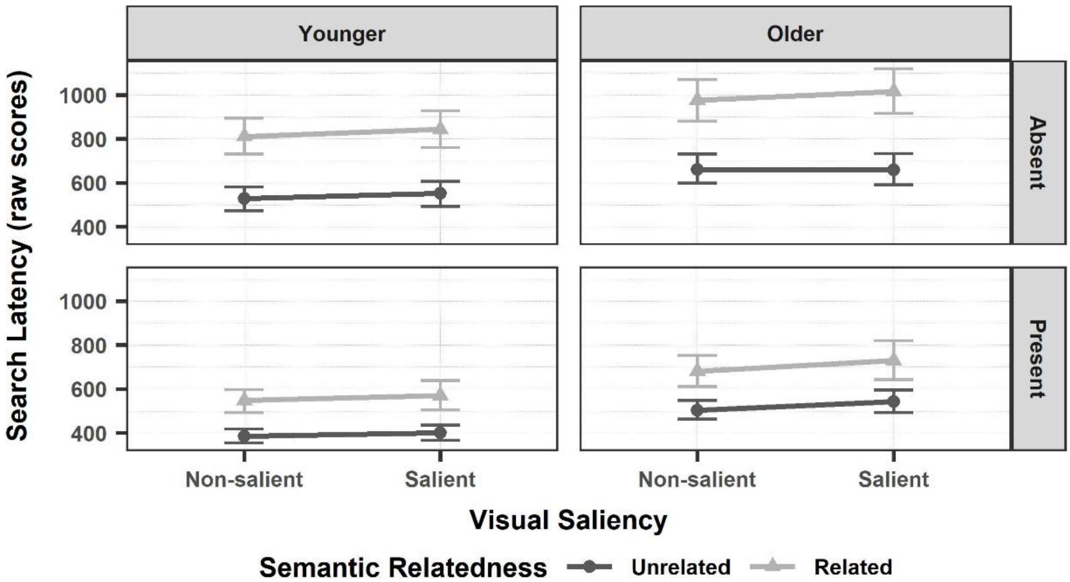

Figure B15. Mean search latency (raw scores, ms) on the critical object.

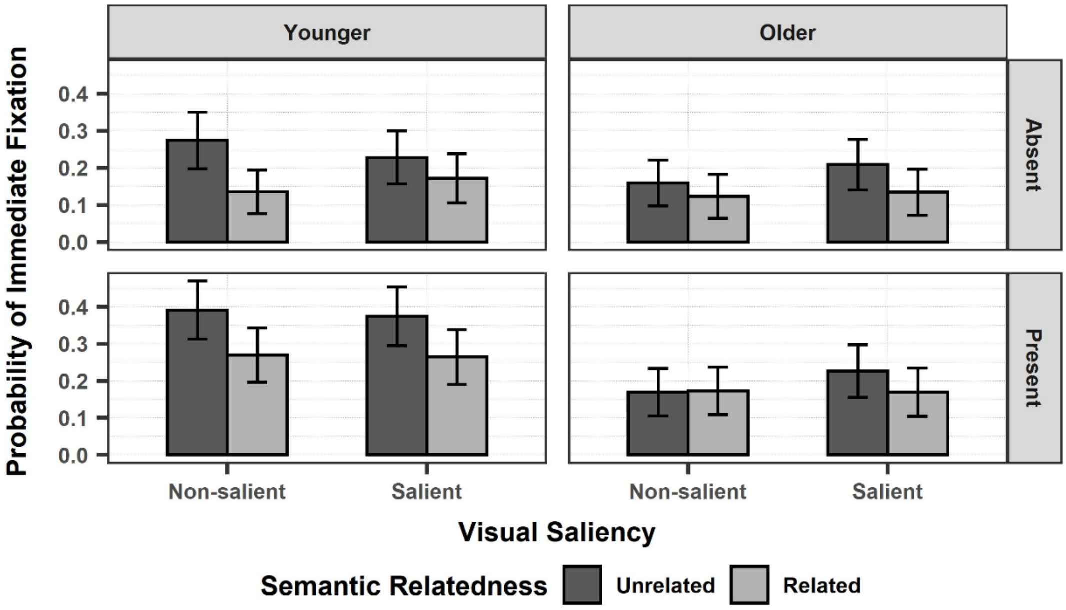

Figure B16. Mean probability of immediate fixation to the critical object (proportions).

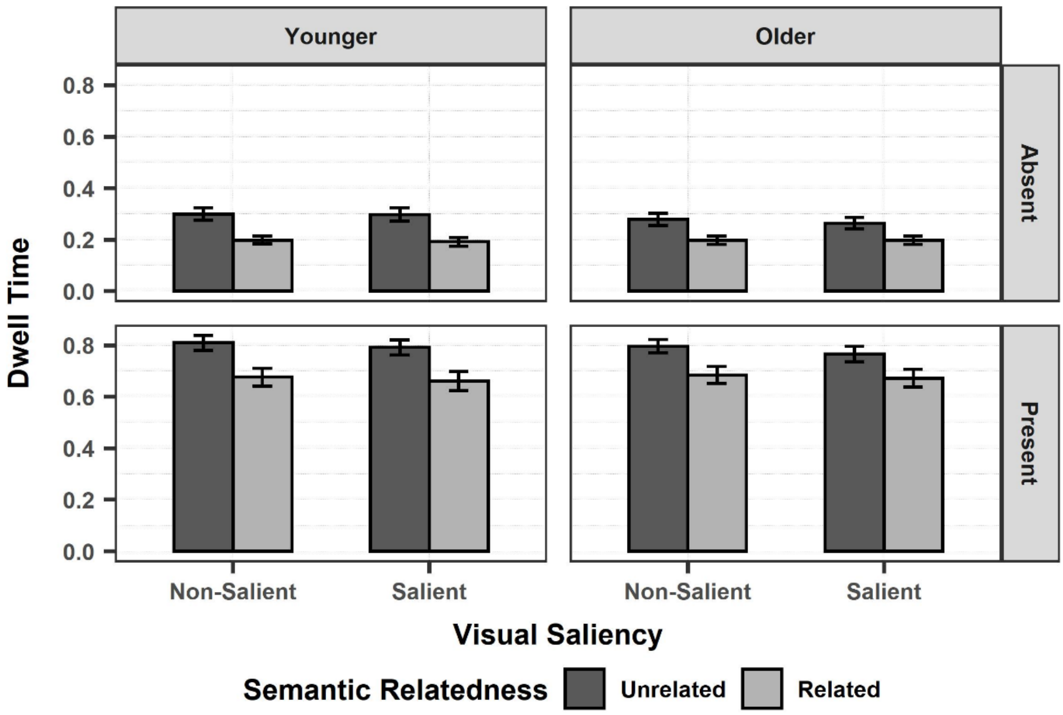

Figure B17. Mean dwell time (proportions) on the critical object.

Experiment 4

The independent variables plotted are: Group (control, AD), on the left and right panel, respectively; Target (Absent, Present), arranged over the rows of the panels; Visual Saliency (Non-salient, Salient), arranged on the x-axis; and Semantic Relatedness (Unrelated, Related), marked using colour: dark grey and light grey, respectively. Visual Similarity (Dissimilar, Similar) is not plotted. Error bars represent 95% confidence intervals around the mean.

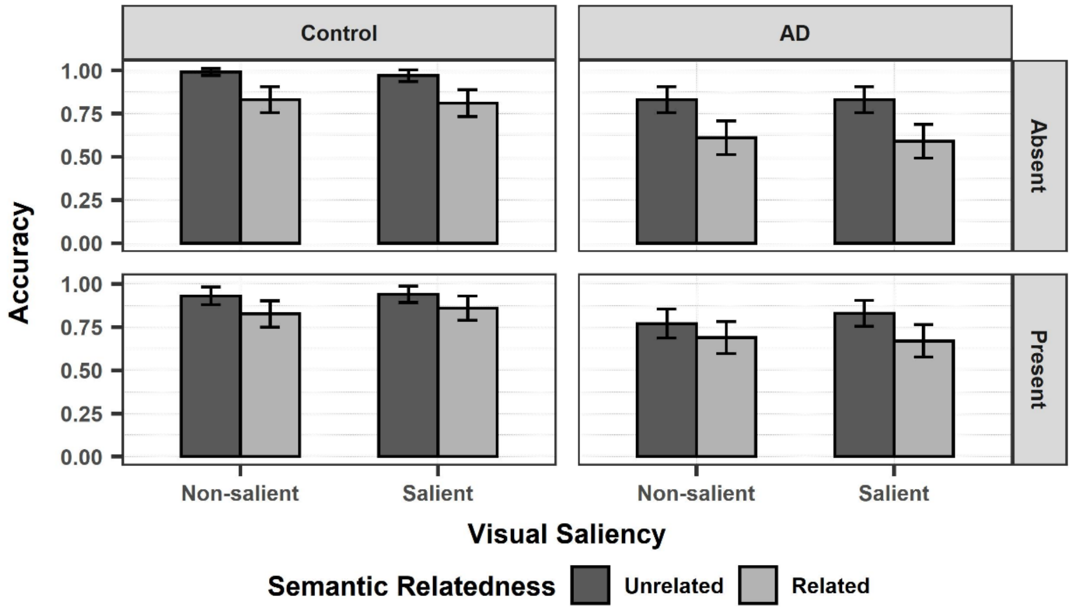

Figure B18. Mean response accuracy (proportions).

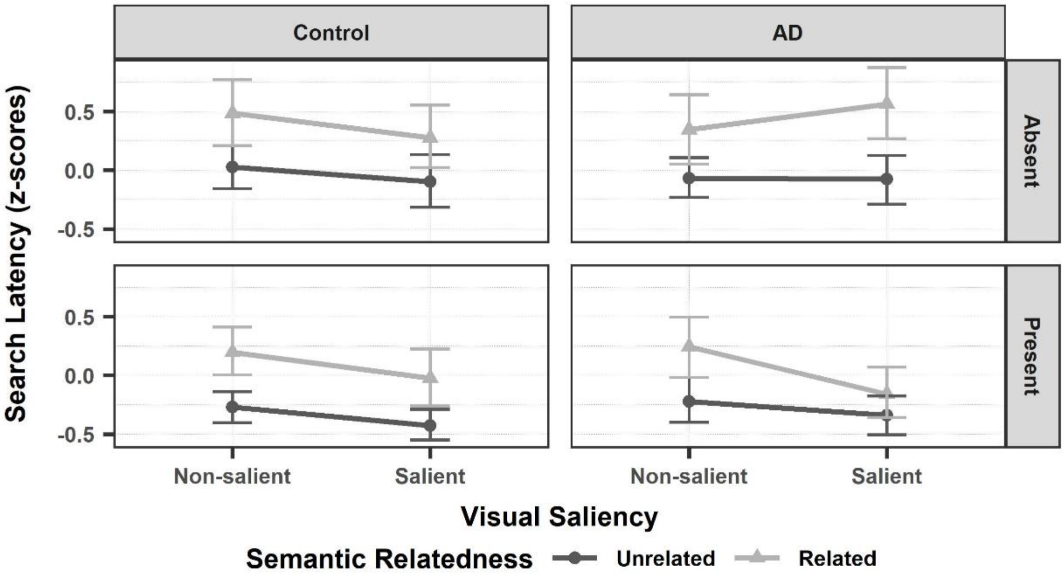

Figure B19. Mean search latency (z-scores) on the critical object.

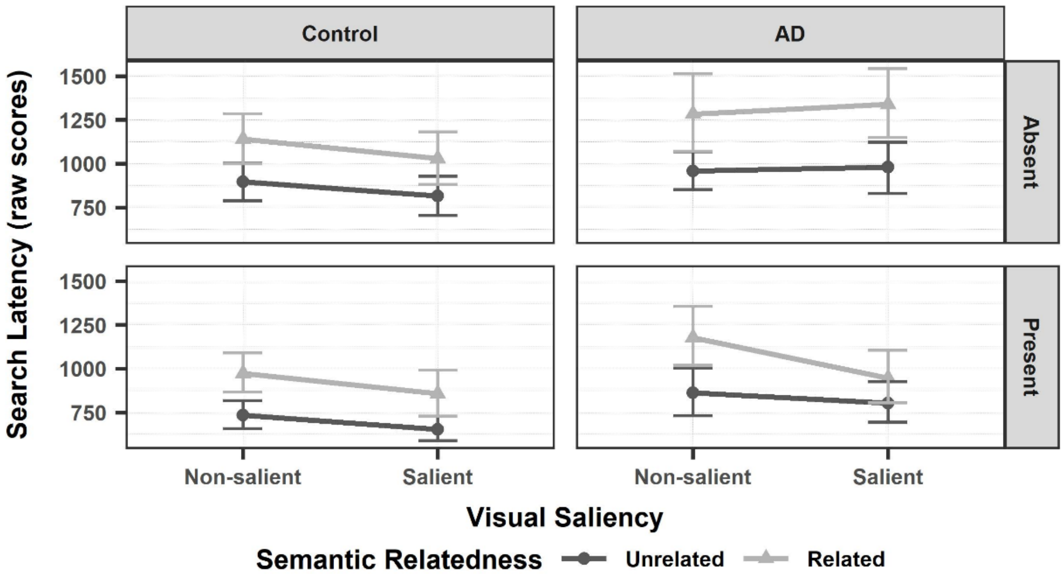

Figure B20. Mean search latency (raw scores, ms) on the critical object.

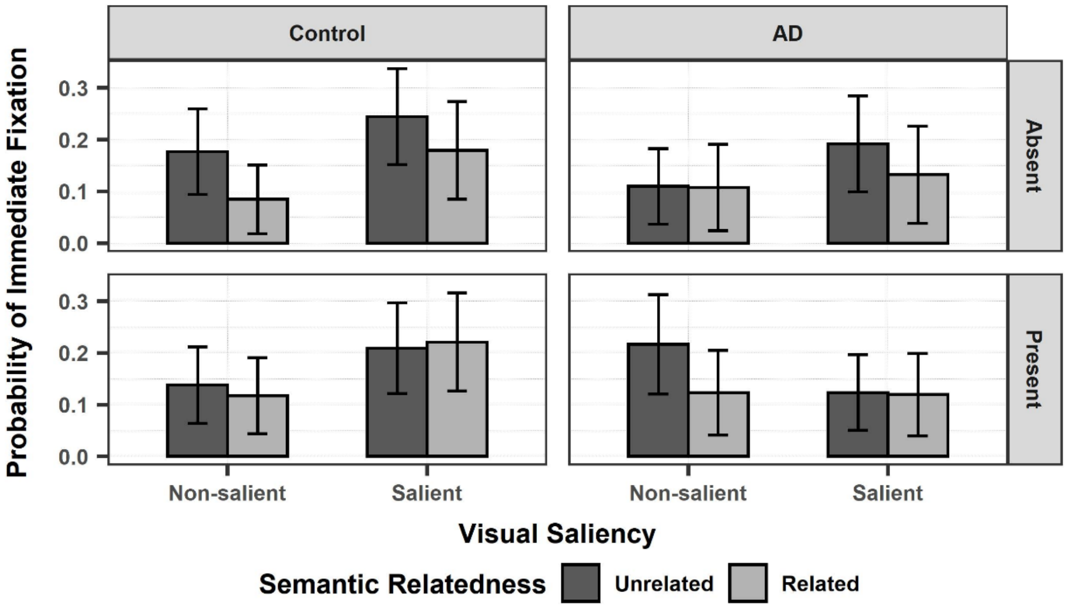

Figure B21. Mean probability of immediate fixation to the critical object (proportions).

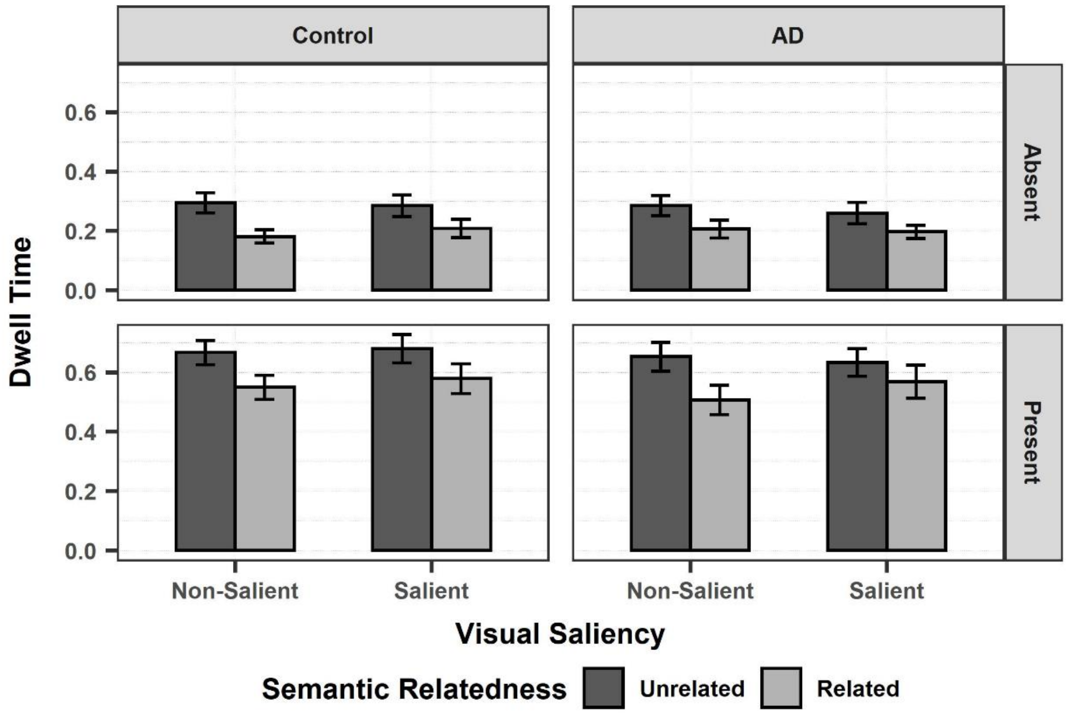

Figure B22. Mean dwell time (proportions) on the critical object.

Experiment 5

The independent variables plotted are: Set Size (3, 5, 7), on the left, central, and right panel, respectively; Visual Similarity (Dissimilar, Similar), arranged over the rows of the panels; Visual Saliency (Non-salient, Salient), arranged on the x-axis; and Semantic Relatedness (Unrelated, Related), marked using colour: dark grey and light grey, respectively. Error bars represent 95% confidence intervals around the mean.

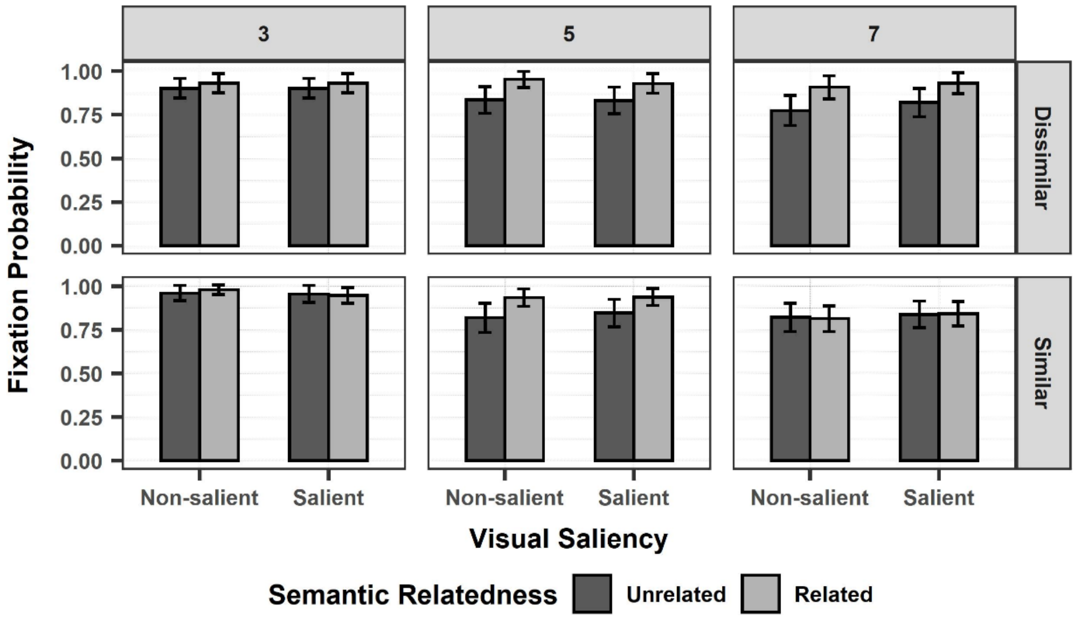

Figure B23. Mean fixation probability (proportions) of the critical object.

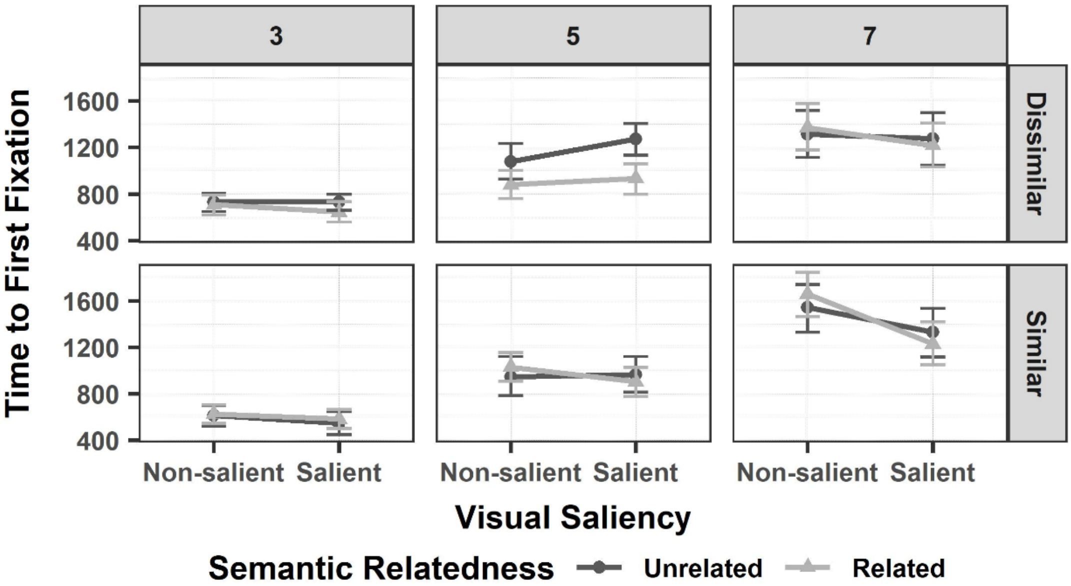

Figure B24. Mean time to first fixation (ms) to the critical object.

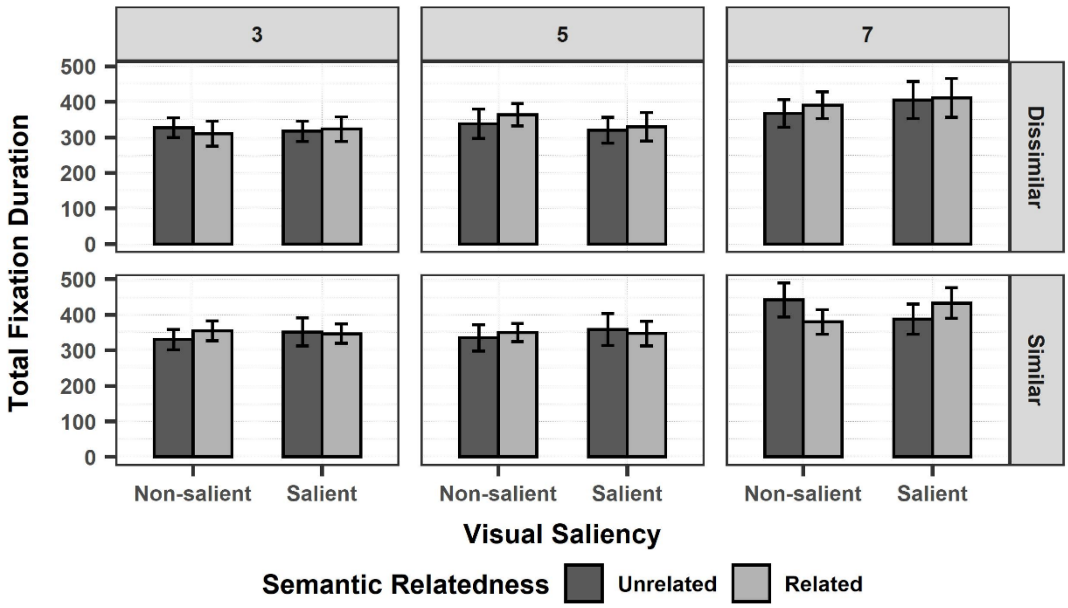

Figure B25. Mean total fixation duration (ms) on the critical object.

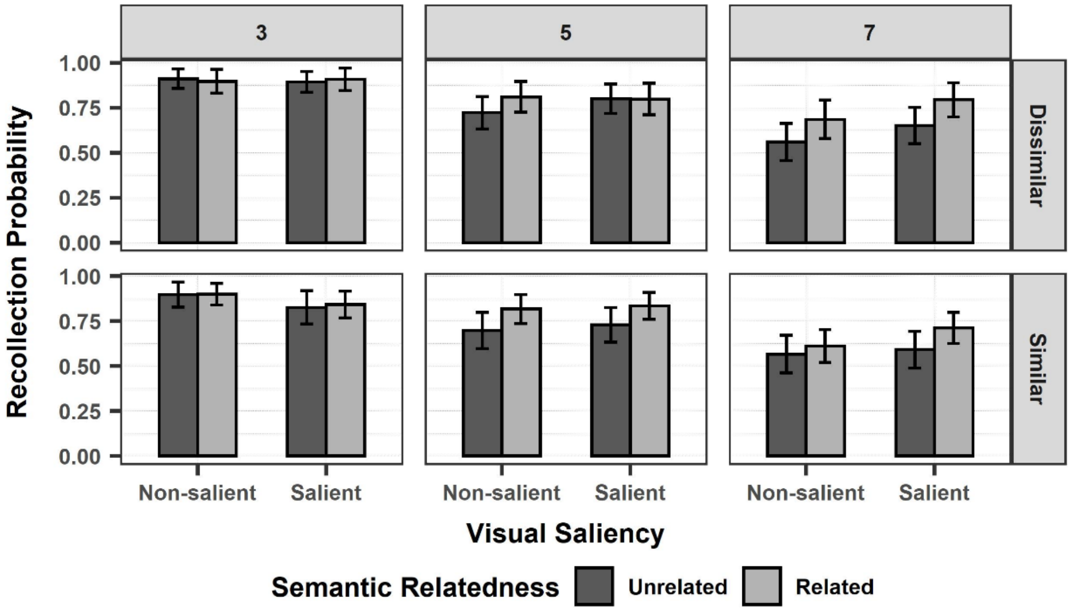

Figure B26. Mean recollection probability (proportions) on the critical object.

Experiment 6

The independent variables plotted are: Group (younger, older), on the left, and right panel, respectively; Visual Similarity (Dissimilar, Similar), arranged over the rows of the panels; Visual Saliency (Non-salient, Salient), arranged on the x-axis; and Semantic Relatedness (Unrelated, Related), marked using colour: dark grey and light grey, respectively. Error bars represent 95% confidence intervals around the mean.

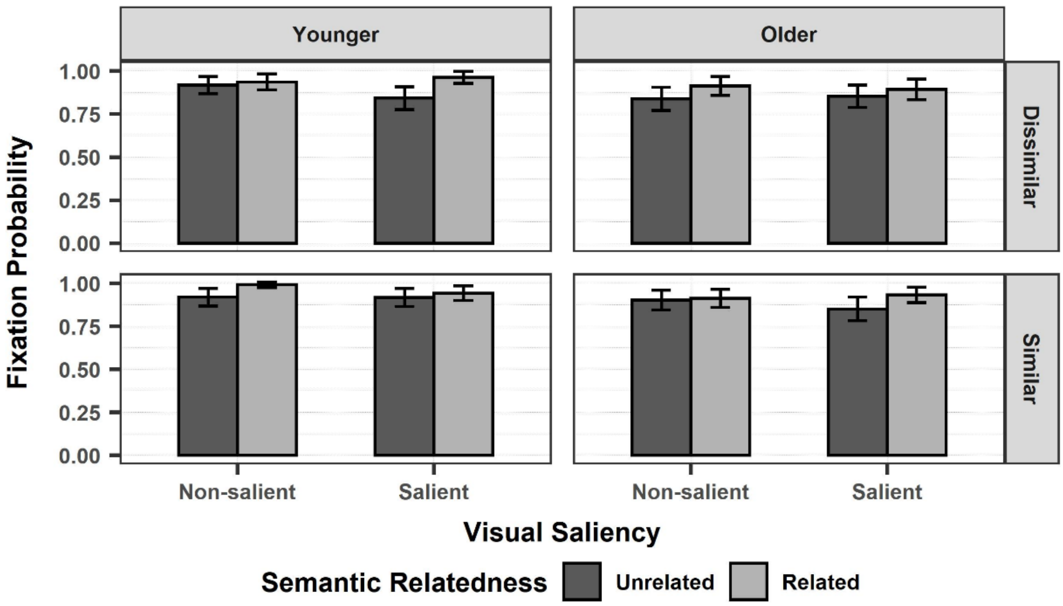

Figure B27. Mean fixation probability (proportions) of the critical object.

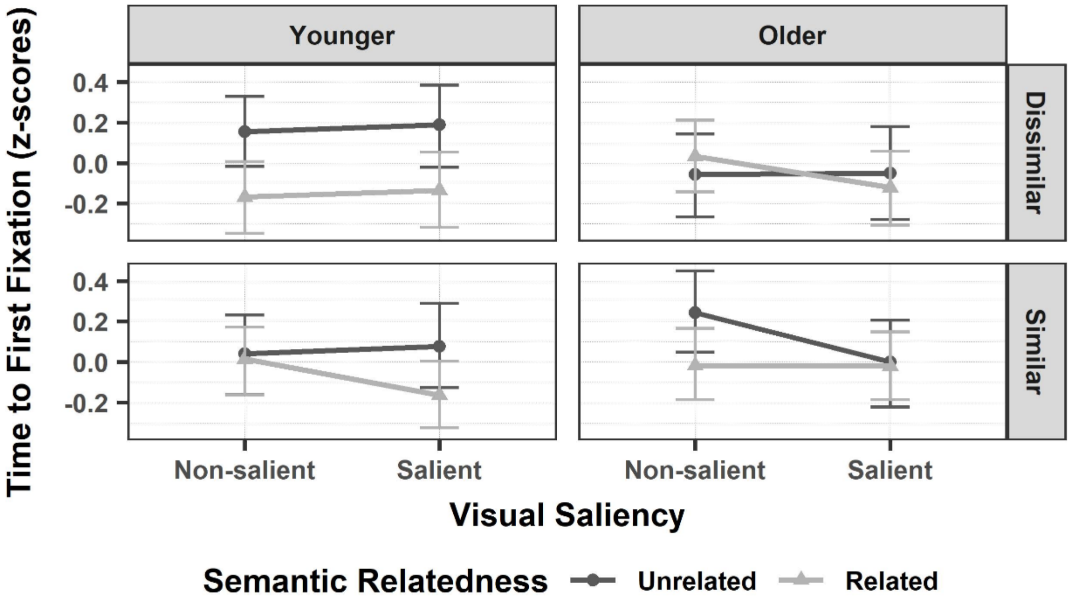

Figure B28. Mean time to first fixation (z-scores) to the critical object.

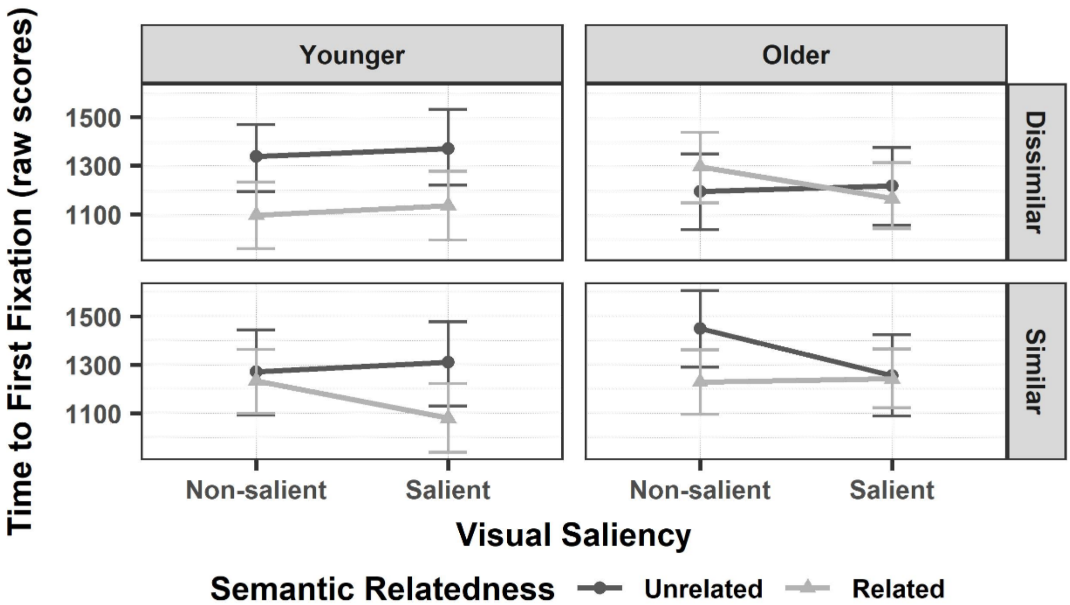

Figure B29. Mean time to first fixation (raw scores) to the critical object.

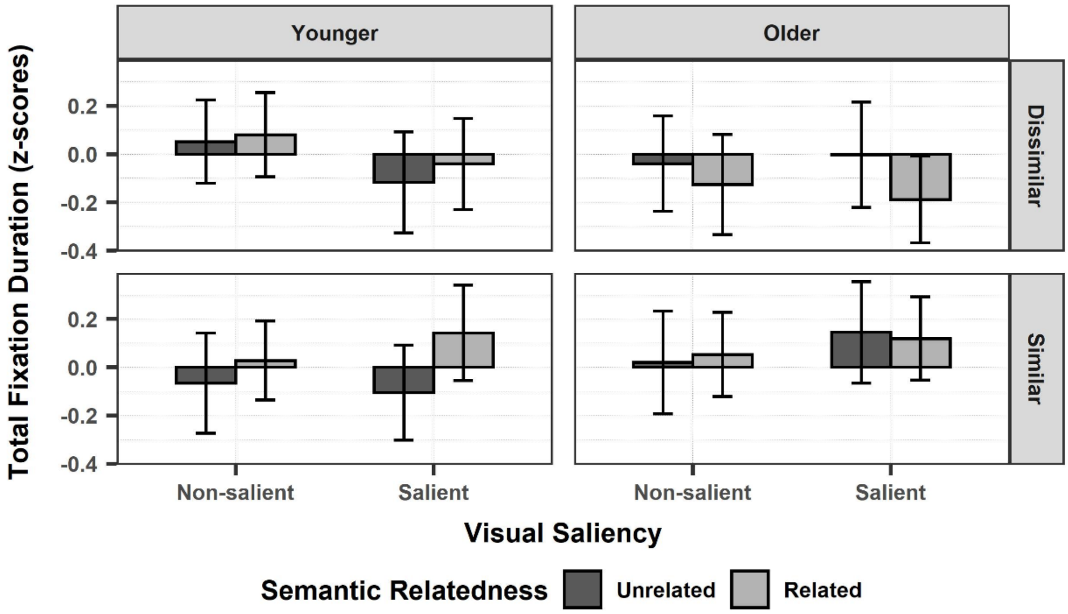

Figure B30. Mean total fixation duration (z-scores) on the critical object.

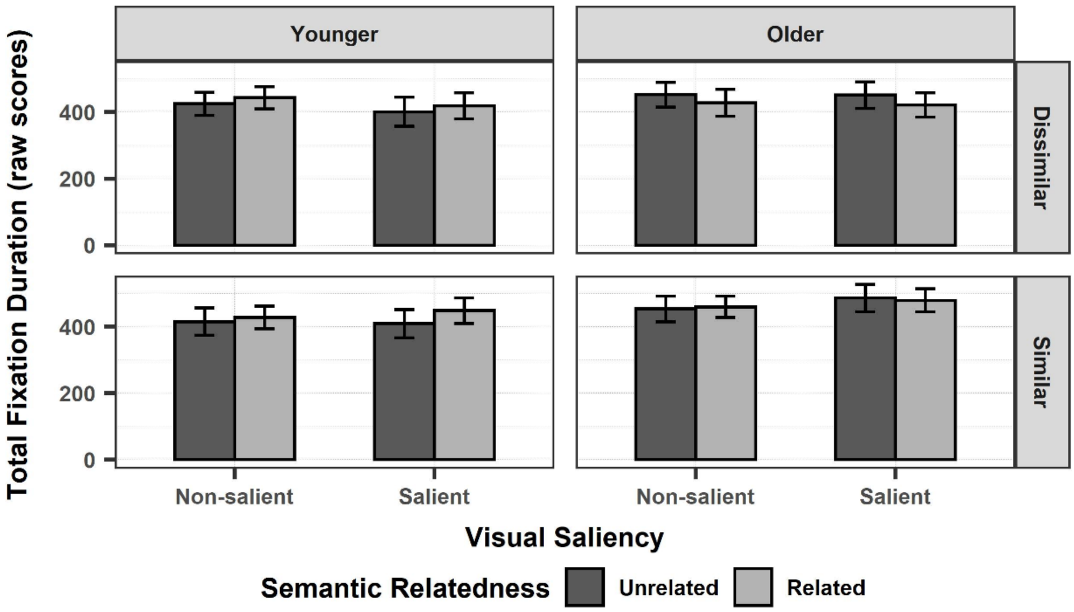

Figure B31. Mean total fixation duration (raw scores) on the critical object.

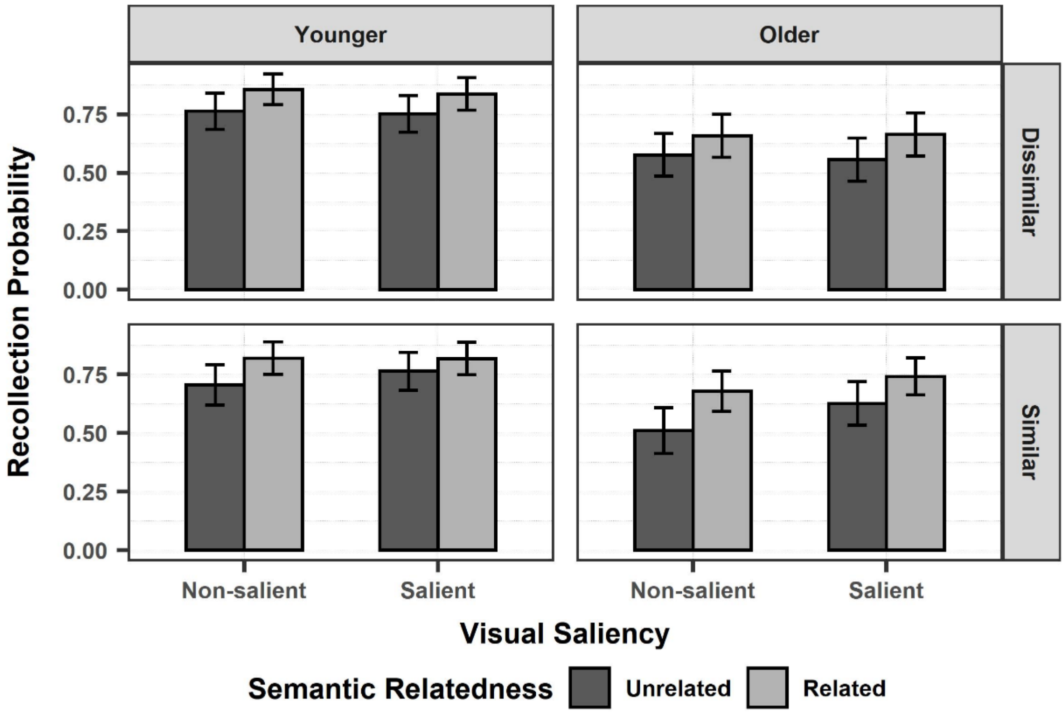

Figure B32. Mean recollection probability (proportions) on the critical object.

Supplemental materials C – Lists of experimental arrays

Table C1

Three-, Five-, and Seven-object Experimental Arrays (with the Target Names for the Target-present and -absent Trials of the Search Task)

Condition	Target name: Present-trials[a]	Target name: Absent-trials	Distractor object: Set size 3	Distractor object: Set size 5[b]	Distractor object: Set size 7
Related	shark (squalo)[c]	prawn (gambero)	crab, squid (granchio, calamaro)	dolphin, starfish (delfino, stella marina)	oyster, swordfish
Unrelated			shirt, trousers (camicia, pantalone)	hat, scarf (cappello, sciarpa)	shoe, sock
Related	raspberry (lampone)	banana (banana)	pineapple, melon (ananas, melone)	pear, mango (pera, mango)	lemon, avocado
Unrelated			rhinoceros, tiger (rinoceronte, tigre)	giraffe, panda (giraffa, panda)	cheetah, squirrel
Related	bowl (ciotola)	colander (scolapasta)	blender, microwave (frullatore, forno a microonde)	fridge, sponge (frigorifero, spugna)	spatula, funnel
Unrelated			skunk, zebra (puzzola, zebra)	porcupine, turtle (porcospino, tartaruga)	bear, moose
Related	bed (letto)	dresser (cassettiera)	mattress, pillow (materasso, cuscino)	candle, lamp (candela, lampada)	couch, fireplace
Unrelated			cauliflower, potato (cavolfiore, patata)	cucumber, lettuce (cetriolo, lattuga)	cabbage, carrot
Related	basketball (palla da basket)	treadmill (tapis roulant)	baseball, volleyball (palla da baseball, palla da pallavolo)	skate, football (pattini, palla da rugby)	paddle, skis
Unrelated			harmonica, tambourine (armonica, tamburello)	banjo, cymbals (bangio, piatti)	accordion, drum
Related	plunger (sturalavandino)	drill (trapano)	screwdriver, hammer (cacciavite, martello)	shovel, wrench (pala, chiave inglese)	wheelbarrow, axe
Unrelated			necklace, bracelet (collana, bracciale)	bag, wallet (borsone, portafogli)	ring, glasses

Condition	Target name: Present-trials	Target name: Absent-trials	Distractor object: Set size 3	Distractor object: Set size 5	Distractor object: Set size 7
Related	knee (ginocchio)	nose (naso)	elbow, leg (gomito, gamba)	foot, shoulder (piede, spalla)	arm, hand
Unrelated			cello, piano (violoncello, pianoforte)	flute, trombone (flauto, trombone)	saxophone, trumpet
Related	tomato (pomodoro)	mushroom (fungo)	celery, onion (sedano, cipolla)	courgette, garlic (zucchini, aglio)	aubergine, olive
Unrelated			curtain, globe (tenda, mappamondo)	bench, mirror (panca, specchio)	aquarium, painting
Related	violin (violino)	harp (arpa)	cello, piano (violoncello, pianoforte)	flute, trombone (flauto, trombone)	saxophone, trumpet
Unrelated			pineapple, melon (ananas, melone)	pear, mango (pera, mango)	lemon, avocado
Related	owl (gufo)	chicken (gallina)	eagle, vulture (aquila, avvoltoio)	duck, pigeon (papera, piccion)	ostrich, parrot
Unrelated			truck, motorcycle (camion, motocicletta)	helicopter, bus (elicottero, pullman)	boat, train
Related	sunglasses (occhiali da sole)	watch (orologio da polso)	necklace, bracelet (collana, bracciale)	bag, wallet (borsone, portafogli)	ring, glasses
Unrelated			lipstick, perfume (rossetto, profumo)	deodorant, toothbrush (deodorante, spazzolino)	razor, tweezers
Related	armour (armatura)	arrow/shield[d] (freccia/NA)	cannon, bullet (cannone, proiettile)	knife, sword (coltello, spada)	tank, spear
Unrelated			mattress, pillow (materasso, cuscino)	candle, lamp (candela, lampada)	couch, fireplace

Condition	Target name: Present-trials	Target name: Absent-trials	Distractor object: Set size 3	Distractor object: Set size 5	Distractor object: Set size 7
Related	comb (pettine)	soap (sapone)	lipstick, perfume (rossetto, profumo)	deodorant, toothbrush (deodorante, spazzolino)	razor, tweezers
Unrelated			screwdriver, hammer (cacciavite, martello)	shovel, wrench (pala, chiave inglese)	wheelbarrow, axe
Related	bee (ape)	cockroach (scarafaggio)	butterfly, ant (farfalla, formica)	dragonfly, spider (libellula, ragno)	ladybird, scorpion
Unrelated			baseball, volleyball (palla da baseball, palla da pallavolo)	skate, football (pattini, palla da rugby)	paddle, skis
Related	pen (penna)	calculator (calcolatrice)	crayon, pencil (pastello, matita)	folder, envelope (cartella, busta)	notebook, scissors
Unrelated			plate, spoon (piatto, cucchiaio)	knife, ladle (coltello, mestolo)	broom, mop
Related	balloon (palloncino)	swing (altalena)	kite, tricycle (aquiline, triciclo)	doll, skateboard (bambola, skateboard)	trampoline, scooter
Unrelated			elbow, leg (gomito, gamba)	foot, shoulder (piede, spalla)	arm, hand
Related	laptop (computer portatile)	television (televisione)	printer, scanner (stampante, fotocopiatrice)	camera, telephone (macchina fotografica, telefono)	hoover, hairdryer
Unrelated			belt, jeans (cintura, pantaloni)	glove, tie (guanto, cravatta)	sandal, slipper
Related	shorts (pantaloncini)	coat (cappotto)	shirt, trousers (camicia, pantalone)	hat, scarf (cappello, sciarpa)	shoe, sock
Unrelated			crab, squid (granchio, calamaro)	dolphin, starfish (delfino, stella marina)	oyster, swordfish

Condition	Target name: Present-trials	Target name: Absent-trials	Distractor object: Set size 3	Distractor object: Set size 5	Distractor object: Set size 7
Related	car (automobile)	airplane (aeroplano)	truck, motorcycle (camion, motocicletta)	helicopter, bus (elicottero, pullman)	boat, train
Unrelated			pot, teapot (pentola, teiera)	apron, kettle (grembiule, bollitore)	mixer, toaster
Related	elephant (elefante)	mouse (topo)	rhinoceros, tiger (rinoceronte, tigre)	giraffe, panda (giraffa, panda)	cheetah, squirrel
Unrelated			cherries, plum (ciliegie, prugna)	orange, peach (arancia, pesca)	lime, grapes
Related	boot (stivale)	jacket (giacca)	belt, jeans (cintura, pantaloni)	glove, tie (guanto, cravatta)	sandal, slipper
Unrelated			eagle, vulture (aquila, avvoltoio)	duck, pigeon (papera, piccione)	ostrich, parrot
Related	mug (tazza)	tray (vassoio)	pot, teapot (pentola, teiera)	apron, kettle (grembiule, bollitore)	mixer, toaster
Unrelated			butterfly, ant (farfalle, formica)	dragonfly, spider (libellula, ragno)	ladybird, scorpion
Related	stool (sgabello)	armchair (poltrona)	chair, table (sedia, tavolo)	desk, vase (scrivania, vaso)	shelf, bookshelf
Unrelated			flamingo, penguin (fenicottero, pinguino)	peacock, pelican (pavone, pellicano)	rooster, turkey
Related	broccoli (broccolo)	pumpkin (zucca)	cauliflower, potato (cavolfiore, patata)	cucumber, lettuce (cetriolo, lattuga)	cabbage, carrot
Unrelated			kite, tricycle (aquiline, triciclo)	doll, skateboard (bambola, skateboard)	trampoline, scooter

Condition	Target name: Present-trials	Target name: Absent-trials	Distractor object: Set size 3	Distractor object: Set size 5	Distractor object: Set size 7
Related	guitar (chitarra)	clarinet (clarinetto)	harmonica, tambourine (armonica, tamburello)	banjo, cymbals (bangio, piatti)	accordion, drum
Unrelated			lizard, crocodile (lucertola, coccodrillo)	hyena, monkey (iena, scimmia)	fox, lion
Related	seagull (gabbiano)	swan (cigno)	flamingo, penguin (fenicottero, pinguino)	peacock, pelican (pavone, pellicano)	rooster, turkey
Unrelated			blender, microwave (frullatore, forno a microonde)	fridge, sponge (frigorifero, spugna)	spatula, funnel
Related	strawberry (fragola)	apple (mela)	cherries, plum (ciliegie, prugna)	orange, peach (arancia, pesca)	lime, grapes
Unrelated			pig, sheep (maiale, pecora)	cat, dog (gatto, cane)	bull, wolf
Related	cow (mucca)	horse (cavallo)	pig, sheep (maiale, pecora)	cat, dog (gatto, cane)	bull, wolf
Unrelated			celery, onion (sedano, cipolla)	courgette, garlic (zucchini, aglio)	aubergine, olive
Related	kangaroo (canguro)	rabbit (coniglio)	lizard, crocodile (lucertola, coccodrillo)	hyena, monkey (iena, scimmia)	fox, lion
Unrelated			printer, scanner (stampante, fotocopiatrice)	camera, telephone (macchina fotografica, telefono)	hoover, hairdryer
Related	fork (forchetta)	pan (padella)	plate, spoon (piatto, cucchiaio)	knife, ladle (coltello, mestolo)	broom, mop
Unrelated			crayon, pencil (pastello, matita)	folder, envelope (cartella, busta)	notebook, scissors

Condition	Target name: Present-trials	Target name: Absent-trials	Distractor object: Set size 3	Distractor object: Set size 5	Distractor object: Set size 7
Related	clock (orologio)	rug (tappeto)	curtain, globe (tenda, mappamondo)	bench, mirror (panca, specchio)	aquarium, painting
Unrelated			cannon, bullet (cannone, proiettile)	knife, sword (coltello, spada)	tank, spear
Related	gorilla (gorilla)	hyppopotamus (ippopotamo)	skunk, zebra (puzzola, zebra)	porcupine, turtle (porcospino, tartaruga)	bear, moose
Unrelated			chair, table (sedia, tavolo)	desk, vase (scrivania, vaso)	shelf, bookshelf

Note. [a] The critical objects are listed in the target name column for target-present trials. The 32 critical objects listed in this table appeared in all the experiments.

[b] In Experiments 3, 4, and 6, participants were presented with five-object arrays only. See also Table C2 (below) for the list of additional critical objects and five-object experimental arrays used for these experiments.

[c] In parenthesis, the Italian translation of the objects' names used for Experiment 4 which had native Italian speakers as participants.

[d] Shield replaced arrow as target name for target-absent trials in set size 7.

Table C2

Additional Five-object Experimental Arrays (with the Target Names for the Target-present and -absent Trials of the Search Task) used for Experiments 3, 4, and 6

Condition	Target name: Present-trials[a]	Target name: Absent-trials	Distractor object			
Related	hairdryer (asciugacapelli)[b]	radio (radio)	hoover (aspirapolvere)	speaker (cassa)	computer (computer)	iron (ferro da stiro)
Unrelated			trumper (tromba)	triangle (triangolo)	drum (tamburo)	gong (gong)
Related	ear (orecchio)	lips (labbra)	arm (braccio)	eye (occhio)	hand (mano)	nail (unghia)
Unrelated			ladder (scala)	pitchfork (forcone)	hose (tubo)	wheelbarrow (carriola)
Related	lion (leone)	wolf (lupo)	bull (toro)	fox (volpe)	bear (orso)	cheetah (ghepardo)
Unrelated			coconut (cocco)	avocado (avocado)	grapes (uva)	blackberry (more)
Related	kiwi (kiwi)	lemon (limone)	coconut (cocco)	avocado (avocado)	grapes (uva)	blackberry (more)
Unrelated			bull (toro)	fox (volpe)	bear (orso)	cheetah (ghepardo)
Related	chainsaw (motosega)	axe (ascia)	ladder (scala)	pitchfork (forcone)	hose (tubo)	wheelbarrow (carriola)
Unrelated			arm (braccio)	eye (occhio)	hand (mano)	nail (unghia)
Related	funnel (imbuto)	sieve (setaccio)	toaster (tostapane)	spatula (spatola)	corkscrew (cavatappi)	mixer (robot da cucina)
Unrelated			maize (panocchia)	cabbage (cavolo)	radish (ravanello)	asparagus (asparagi)
Related	saxophone (sassofono)	accordion (fisarmonica)	trumpet (tromba)	triangle (triangolo)	drum (tamburo)	gong (gong)
Unrelated			hoover (aspirapolvere)	speaker (cassa)	computer (computer)	iron (ferro da stiro)
Related	aubergine (melanzana)	carrot (carota)	maize (panocchia)	cabbage (cavolo)	radish (ravanello)	asparagus (asparagi)
Unrelated			toaster (tostapane)	spatula (spatola)	corkscrew (cavatappi)	mixer (robot da cucina)

Note. [a] The critical objects are listed in the target name column for target-present trials. The 8 critical objects listed in this table appeared in Experiment 3, 4, and 6 only.

[b] In parenthesis, the Italian translation of the objects' names used for Experiment 4 which had native Italian speakers as participants.